A PHOTO-ELASTIC STUDY OF STRESS DISTRIBUTION IN SHIP TRANSVERSE BULKHEADS

Arthur Ramos Figueiredo
Daniel Angelo Marangiello
and
Walter Vilela Guerra

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ARTHUR RAMOS FIGUEIREDO

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SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
NAVAL ENGINEER

and

WALTER VILELA GUERRA

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN
NAVAL ARCHITECTURE AND
MARINE ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MAY 1956

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Submitted to the Department of Naval Architecture and Marine Engineering on 21 May 1956 in partial fulfillment of the requirements for the degree of Naval Engineer

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ABSTRACT

This thesis is a continuation of the work of Rockwell Holman, reference (13). The general objective is the determination of data pertinent to the design of ship transverse bulkheads. Specifically, this thesis investigates the distribution of load between side and bottom supports for an unstiffened bulkhead subjected to a concentrated load applied centrally in its plane. The effect of a vertical centerline stiffener on this distribution is also investigated.

The photo-elastic approach was used and the Shear Difference method employed in computing the shear stress distribution over the side support.

Two rectangular plates of identical dimensions were used. Isochromatics were recorded by photographing the loaded Catalin 61-893 plate. Isoclinics were obtained by tracing the pattern shown on the less sensitive Plexiglass plate.

Curves were obtained for the shear stress distribution at the sides for the unstiffened plate supported at sides only, and at sides and bottom, and for the stiffened plate supported at sides and bottom.

Overall accuracy was determined to be within 10%.

The addition of the stiffener had little effect on the shape of the shear distribution, but it reduced appreciably the part of the load taken by the bottom.

The validity of these results should be investigated further by photo-elastic studies using plates of various aspect ratios with several stiffener arrangements.

Thesis Supervisor: William M. Murray

Title: Professor of Mechanical Engineering

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ACKNOWLEDGMENT

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Cambridge, Massachusetts
May 21, 1956

Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Sir:

In accordance with the requirements for the Degrees of Naval Engineer and Master of Science in Naval Architecture and Marine Engineering, we herewith submit a thesis entitled: "A Photo-Elastic Study of Stress Distribution in Ship Transverse Bulkheads".

Respectfully yours,

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I. INTRODUCTION

Whenever a structure is being designed all efforts are made by the designer toward a least weight solution that still fulfills the safety requirements. A solution of this kind can only be obtained if reliable formulation is available, based on results of careful theoretical and experimental studies of stress distribution. By the use of available technique and the simulation of the same conditions as those which exist in a ship's transverse bulkhead, we attempted to draw reliable conclusions concerning quantitative and qualitative characteristics of the stresses in the supports of a plate subjected to a concentrated co-planar compressive load.

One of the best techniques available is that of using the photoelastic theory to determine stress patterns through isoclinics and isochromatic lines. This is the technique used in our experiments. By supporting the plate at the sides and bottom, we attempted to make conditions similar to a ship's transverse bulkhead. Furthermore, the simulation was improved by providing the plate with vertical centerline stiffeners for one part of the experiment.

The experimental work in this thesis was simplified a great deal by the fact that most of the apparatus needed was already available from previous work.[13] Recommendations and results from this previous work were also considered.

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ous aspect ratios. The current practice in this matter is given by the Bureau of Ships which specifies that "stiffeners shall be arranged and designed so that when acting with a strip of bulkhead plating not exceeding sixty times the plating thickness they will be adequate to support that part of concentrated vertical loads which cannot be considered as being distributed to the bulkhead boundaries through shear in the bulkhead plating. The vertical load which is considered to be distributed to the boundaries by shear should be based upon a shear stress in the plating for one deck height (or where no deck is connected below the point of application of the load, then 7 feet) of about one-half the critical shear stress for the thickness of plating and size of panel in question." The check of the validity of such a specification was one of our goals in this thesis.

Several studies of plates subjected to normal and co-planar loads have been made. The investigation of failure by instability accounts for most of the literature in this field and the problem involving buckling loads of stiffened and unstiffened rectangular plates seems to be steadily approaching a satisfactory stage. Considerable work, both experimental and analytical, on buckling and failure of rectangular plates in compression[20], their behavior under the action of shearing forces[3], and also, how they behave after buckling[7], has been reported in the literature.

The stress distribution in flat plates at loads below critical have had less experimental attention and most investigation has been done analytically. Civil engineers have worked on the determination of stress distribution in deep beams[5]. This work is applicable to ship structure as well.

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Photoelasticity has been used a great deal to determine stress distribution in beams. Several theories and statements have been checked by the use of this valuable tool. A quite remarkable reference to the use of this technique is the investigation of stresses in a rectangular bar by means of polarized light[8] in 1912. The purpose of this study was to verify the results of Saint-Venant concerning the parabolic distribution of shear in a long bar of rectangular cross section at a distance from the points of loading.

The first attempt to investigate the stress distribution on a stiffened plate by the use of photoelasticity was presented, to the best of the writers' knowledge, by reference[13] which limited the extent of the study to determination of the isoclinic pattern for three aspect ratios.

Several methods are available for determination of stresses. In reference[6], for instance, a problem somewhat similar to ours was studied, namely, "the stress field of a plane plate reenforced by a longitudinal girder and subjected to tension in a direction parallel with the girder". Professor Hovgard's method was to take the average value for shearing stresses between the girder and the plate at any section. He then obtained an expression for the relative displacement from the difference caused by these average stresses between plate and girder and the integral expression for the total elastic work in the system. From this, by the method of variation, the stresses were determined. In reference[6], the actual instead of average stress was used by determining analytically the stress field. However, a continuously attached girder presented a quite involved mathematical analysis and caused the authors to replace the continuous attached girder by one

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The method used in our work was the shear difference method[9], which is based on the well-known differential equations of equilibrium in Cartesian coordinates. This method is considered to be the most powerful, direct and general of all available methods for the determination of normal stresses and deserves much wider use than it has received. It is relatively fast and simple and gives results of high accuracy. It is replacing all other methods for the determination of the separate normal or principal stresses across a section.*

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II. PROCEDURE

The principal objective of this thesis was to determine the shear stress distribution on the side boundaries of a plate loaded in its own plane, and the variation of this stress distribution brought about by adding support on the bottom and finally by adding a centerline stiffner.

The photoelastic approach was used and calculations were made by use of the so-called Shear Difference Method. This method called for the determination of isoclinics and isochromatic lines on the model.

Two models of different materials were used. For the isochromatics, Catalin 61-893, a relatively sensitive material was used. A Plexiglass model was used to determine isoclinics because its low sensitivity made this determination easier. The plates were loaded on a special loading frame by a concentrated force on the centerline. A common load of 1650 lbs was used on all experiments because this load, we felt, would produce the number of lines needed for accuracy without critically straining the model. Four different conditions were examined; the plate supported on sides only, on sides and bottom, and each for the unstiffened and stiffened cases. The stiffners were attached to the plate by using a special solvent, Pennacolite Adhesive G-1124, manufactured by the Koppers Company, Inc., Pittsburgh. An attempt was made to obtain with strain gages the load transmitted by the stiffener. The method, however, did not prove successful.

The determination of the isoclinics was made by using the Plane Polariscope Arrangement with white light. The isoclinics appeared as dark lines on the ground glass viewing screen. The load was varied until the best contrast was obtained, as isoclinics are independent of the load magni-

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tude within the elastic limit.

The isoclinics were obtained at intervals of 10 degrees by simultaneously rotating counterclockwise both polarizer and analyzer through that angle, and drawing them on tracing paper attached to the viewing screen.

The isochromatics were obtained by photography, using a leased Polaroid camera. Two different arrangements were used with monochromatic light. The Standard or Crossed Circular Polariscope produced a dark field with the dark isochromatic lines corresponding to zero and integral orders of interference, while the Mixed Setup with the light field yielded dark isochromatics of half orders.

Because of the large size of the model relative to the lens system of the polariscope, it was not possible to photograph the whole model in a single picture. Pictures were taken of the sides for calculation purposes, and of the center to show the degree of alignment of loading.

With the data thus obtained, curves of direction of maximum principal stress and of the value of fringe orders were plotted. From these curves the shear stress distribution was obtained as shown in the Appendix. A more detailed discussion of the procedure can also be found in the Appendix.

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III. RESULTS

1. With the unstiffened plate supported at sides only and an applied load of 1650 pounds, the computed value of shear reaction on each side was 744 pounds.

2. With the unstiffened plate supported at sides and bottom and an applied load of 1650 pounds, the computed value of shear reaction on each side was 382 pounds.

3. With the stiffened plate supported at sides and bottom and an applied load of 1650 pounds, the computed value of shear reaction on each side was 451 pounds.

4. The distribution of shear stress over the plate edge for the three conditions of restraint is shown in Figure 1. The effect of the added bottom support was to displace the shear stress distribution curve toward the top of the plate.

5. It was found that the addition of the stiffener with the bottom support has the effect of increasing the side shear reaction.

6. Isochromatic and isoclinic patterns for the three conditions of restraint were obtained and are shown in the Appendix.

7. The attempt to use strain gages for obtaining the load taken by the stiffener proved inconclusive.

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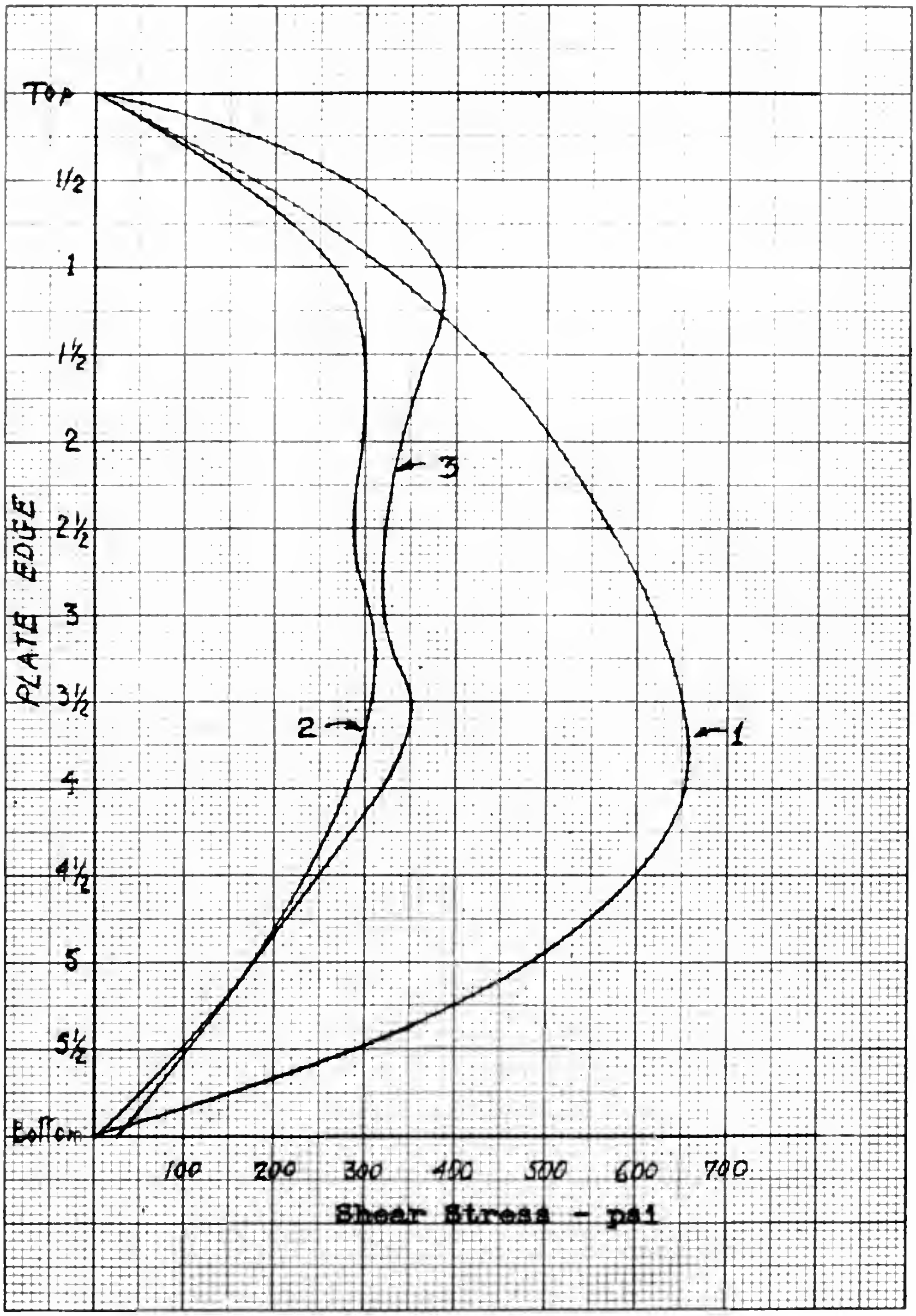

FIGURE I
SHEAR STRESS DISTRIBUTION
1 - Unstiffened plate supported at sides
2 - Unstiffened plate supported at sides and bottom
3 - Stiffened plate supported at sides and bottom

IV. DISCUSSION OF RESULTS

In order to evaluate the results of the experiment, it is necessary to consider the degree of accuracy of the methods used. This accuracy is dependent upon the precision of each step in the experimental procedure, namely, the measurement of the applied external load and the determination of the internal stress distribution.

The load cell and the Baldwin Indicator used to measure the external load applied through the load pin was estimated to have been accurate within 2%.

The determination of the stress distribution was dependent upon photo-elastic results and, therefore, its accuracy was limited by the difficulties encountered.

The fringe constant as determined from the tensile model test was 82.7. All references indicate a fringevalue of 86.0 for the material used. This difference can be attributed either to experimental errors or to a difference in the material itself. This difference, however, will have no effect on the shapes of the computed shear stress distribution, as the same value is used throughout. The apparent accuracy of the shear difference method will be affected, since the value of the shear reaction at the plate sides is directly proportional to the value of the fringe constant.

The most inaccurate part of the experiment is believed to have been the determination of the isoclinic lines. These lines appeared as broad bands at some angles and as very faint lines at others, making the exact tracing of the pattern extremely difficult.

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Little difficulty was experienced in the determination of the isochromatics, however, exact centering of the load was never completely attained.

Edge effects present in the top and bottom edges of the plate changed slightly the isochromatic pattern in this vicinity and obscured some isotropic points, but should not have influenced the values of the fringe orders at the sides.

The use of two plates might have introduced some error because the side restraint might not have been exactly reproduced. It is felt, however, that this possible error was of minor order.

It was possible, in the case of the unstiffened plate supported at the sides only, to check the overall accuracy of the method, since the applied load should have equalled the total reaction. The applied load was measured as 1650 pounds, and the total reaction was computed as 1488 pounds. The overall experimental error, then, was 162 pounds or 9.8%.

By the addition of bottom support the total side reaction was reduced from 1488 pounds to 764 pounds, a reduction of 48.8% as should be expected.

With this same condition of restraint and the addition of a vertical centerline,stiffener, the total shear reaction increased to 902 pounds, an 18.1% increase.

At first thought this might seem unreasonable because the addition of the stiffener would apparently increase the share of the load taken by the bottom. This, however, was not the case. The share of the load taken by the bottom is proportional to the deflection that the plate would have if there was no bottom support. The addition of the stiff-

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ener naturally increased the bending stiffness of the plate, reducing the deflection that otherwise would have taken place in an unstiffened plate.

The shear stress distribution obtained for the unstiffened plate with side support was approximately parabolic in shape, with the maximum value occurring approximately at .667 h (plate height) from the top.

When bottom support was added, the curve became flatter and was displaced toward the top. Two distinct humps of maximum shear stress were observed located at approximately .250 h and .583 h from the top.

Addition of the centerline stiffener with this same condition of restraint did not cause any marked change in the shape of the stress distribution curve. The increase in shear stress was more pronounced toward the top edge of the plate.

During the loading, the stiffened plate supported at the sides only, failed before the 1650 pound load used in the previous parts of the experiment was attained. It is believed that the failure can be attributed to the tri-axiality of stress developed at the stiffener connection. This is born out by the fact that the crack ran parallel to the stiffener weldment. It is interesting to note that the crack occurred in the plate itself indicating that Pennacolite G-1124 provided a strong bond. Figure XIX shows a close-up of the plate after failure.

One other factor may or may not have affected our results. The plate was stress-relieved in the Laboratory oven to remove any effects of the first two parts of the experiment. During this stress relieving, a small area of the plate became plastic as a result of uneven heating in the oven. Upon rehardening, blotches appeared on the plate surface.

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The plate was reheated to 250° F and allowed to soak for a weekend. This apparently corrected these surface defects as the blotches all but disappeared.

The attempt to obtain the load transmitted through the stiffener was not successful because an improper technique was used. The strain gages indicated only local strain on the stiffener and this strain varied throughout its length. The total load, therefore, could not be evaluated.

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V. CONCLUSIONS

1. The Shear Difference Method, as used in this experiment, yields an overall accuracy within 10%.

2. The addition of a centerline stiffener reduces the part of the load taken by the bottom.

3. The addition of bottom support shows a definite trend in displacing the shear stress distribution curve toward the top edge of the plate. Also, this distribution curve becomes flatter and exhibits two distinct humps as compared with the parabolic shear distribution obtained with the side supports only.

4. The addition of a centerline stiffener does not appreciably affect the shape of this curve; however, the value of the total shear reaction, represented by the area under the curve, is increased.

5. The addition of a stiffener introduces tri-axiality of stress that may become critical at high loadings.

6. Penacolite G-1124 is an effective bonding adhesive in welding Catalin 61-893. This fact makes possible the use of this sensitive photo-elastic material in built-up models.

7. The technique used in evaluating the load transmitted through the stiffener proved unsatisfactory.

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VI. RECOMMENDATIONS

1. It is recommended that this photo-elastic study be continued and that emphasis be placed on:

    a. Utilization of various aspect ratios so that its effect upon the shear stress distribution can be evaluated.

    b. Utilization of more stiffeners symmetrically arranged to verify the trend displayed in this experiment.

2. Future studies should utilize two plates, namely, Catalin 61-893 for determination of isochromatics and a less sensitive material, such as Lucite, for determination of isoclinic lines.

3. An effort should be made to evaluate the load transmitted through the stiffeners. It is believed that this could be accomplished by utilization of several small strain gages mounted at various locations along the length of the stiffeners. In this way the stress distribution over the length of the stiffeners may be determined.

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VII APPENDIX

VII. APPENDIX

A. SUPPLEMENTARY INTRODUCTION

Elements of Photo-Elastic Theory

There are many stress analysis problems in which the deformation is essentially parallel to a plane. These are called two-dimensional problems. Plates of any shape but of constant thickness acted on by forces or couples in the plane of the plate may have such shapes that the stress distributions are very difficult to determine analytically and for such cases the photo-elastic method has proved very useful. In this method, models cut out of a plate of an isotropic transparent material such as glass, celluloid or bakelite are used. It is well known that under the action of stresses these materials become doubly refracting and, if a beam of polarized light is passed through a transparent model under stress, a picture with colored bands or with dark and light fringes may be obtained.

In the following explanation, we regard an ordinary beam of light as consisting of vibrations in all directions transverse to the direction of the ray. By passing the beam through a Nicol prism or a Polaroid disc or by reflecting it from a glass plate covered on one side with black paint, one obtains a more or less polarized beam of light in which transverse vibrations in a definite direction prevail. This is the kind of light used in investigating stress distributions in plates.

In Fig. XIV-A, "abcd" represents a transparent plate of uniform thickness and "O" is the point of intersection with the plate of a beam of polarized light perpendicular to the plate. Suppose that OA represents the plane of vibration of monochromatic light and that the length OA = a represents the amplitude of this vibration. If the

vibration is considered to be simple harmonic, the displacements may be represented by the equation

$$s = a \cos pt \qquad (1)$$

where p is proportional to the frequency of vibration, which depends on the color of the light.

Imagine now that the two principal stresses s_x and s_y, different in magnitude, are applied to the edges of the plate. Due to the difference in the stresses, the optical properties of the plate also become different in the two perpendicular directions. Let v_x and v_y denote the velocities of light in the planes OX and OY respectively. The simple vibration in plane OA is resolved into two components with amplitudes $OB = a \cos\alpha$ and $OC = a \sin\alpha$ in the planes OX and OY respectively, and the corresponding displacements are

$$x = a \cos\alpha \cos pt; \qquad y = a \sin\alpha \cos pt. \qquad (2)$$

If h is the thickness of the plate, the intervals of time necessary for the two component vibrations to cross the plate are

$$t_1 = \frac{h}{v_x} \quad \text{and} \quad t_2 = \frac{h}{v_y} \qquad (3)$$

and vibrations (2) after crossing the plate are given by the equations:

$$x_1 = a \cos\alpha \cos p(t - t_1); \qquad y_1 = a \sin\alpha \cos p(t - t_2). \qquad (4)$$

These components have the phase difference $p(t_2 - t_1)$, due to the difference in velocities (v_x is assumed greater than v_y). Experiments show that the difference of these velocities of light is proportional to the difference in the principal stresses; that is, $v_x - v_y = c(s_x - s_y)$. Then, taking into account the fact that the changes of velocity of the light are very small and denoting by v the velocity of the light when the stresses are zero, we obtain the approximate equation

vibration [illegible] taken to be simple harmonic, the displacement [illegible] can be expressed [illegible] by the formula

$$s = a \cos pt, \qquad (1)$$

where p is proportional to the frequency of vibration, which [illegible] the color of the light.

Imagine now that the two principal stresses s_x and s_y, different in magnitude, are applied to the edges of the plate. Due to the difference in the stresses, the optical properties of the plate also become different in the two perpendicular directions. Let v_x and v_y denote the velocities of light in the planes OX and OY respectively. The simple vibration in plane OA is resolved into two components with amplitudes OB = $a \cos \alpha$ and OC = $a \sin \alpha$ in the planes OX and OY respectively, and the corresponding displacements are

$$x = a \cos \alpha \cos pt; \qquad y = a \sin \alpha \cos pt. \qquad (2)$$

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and [illegible] [illegible] [illegible] squares [illegible].

$$t_2 - t_1 = \frac{h}{v_y} - \frac{h}{v_x} = \frac{h\,(v_x - v_y)}{v_x\, v_y} = \frac{h\,(v_x - v_y)}{v^2} = \frac{hc}{v^2}\,(s_x - s_y), \qquad (5)$$

where c is a constant dependent on the physical properties of the material of the plate.

The difference of the two prinsipal stresses can therefore be found by measuring the difference in phase of the two vibrations. This can be done by bringing them into interference in the same plane. For this purpose, another Nicol prism or Polaroid disc (called the analyzer) is placed behind the plate in such a position as to permit the passage of vibrations in the plane "mn" perpendicular to the plane OA only. The components of the vibrations (4), which pass through the analyzer, have the amplitudes $OB_1 = OB \sin\alpha = a \cos\alpha \sin\alpha = 1/2\ a \sin 2\alpha$ and $OC_1 = OC \cos\alpha = a \sin\alpha \cos\alpha = 1/2\ a \sin 2\alpha$. The resultant vibration in plane "mn" is

$$OC_1 \cos p\,(t - t_2) - OB_1 \cos p\,(t - t_1) =$$

$$= 1/2\ a \sin 2\alpha \cos p\,(t - t_2) - 1/2\ a \sin 2\alpha \cos p\,(t - t_1) =$$

$$= \left(a \sin 2\alpha \sin p\,\frac{t_2 - t_1}{2}\right) \sin p\,\left(t - \frac{t_1 + t_2}{2}\right) \qquad (6)$$

This is a simple harmonic vibration whose amplitude is proportional to $\sin 1/2\ p(t_2 - t_1)$, hence the intensity of the light is a function of the difference in phase $p\,(t_2 - t_1)$ or, from eq. (5) a function of the difference of the two principal stresses.

If the stresses s_x and s_y are equal, t_1 and t_2 are also equal and the amplitude of the resultant vibration (6) is zero, that is, the light is not transmitted at the point O and a dark spot occurs on the screen behind the analyzer. There will be darkness also whenever the angle

$$1/2\ p\,(t_2 - t_1) = n\pi \qquad (7)$$

where n is an integer. The maximum intensity of light will be obtained when the difference in principal stresses is such that

$$1/2\ p(t_2 - t_1) = n\pi + \frac{\pi}{2}$$

By substituting $t_2 - t_1$ from eq. (4) into eq. (7) and then setting

$$\frac{2\pi v^2}{phc} = K_d \qquad (8)$$

one gets

$$s_x - s_y = \frac{2\pi v^2}{phc}\ n = n\ K_d \qquad (9)$$

denoting that there will be darkness whenever the difference of the principal stresses becomes equal to an integral multiple of K_d.

To determine the value of K_d, let us replace the element "abcd" (Fig. XIV-A) under biaxial stress by a strip of similar material under simple tension ($s_y = 0$). By gradually increasing the tensile stress s_x, we obtain a dark picture of the strip on the screen each time eq.(9) is fulfilled. In this manner we can establish experimentally, for a given material of given thickness, the stress corresponding to the interval between two consecutive dark pictures of the specimen. With this information, we can determine the total stress in a strip under tension by counting the number of intervals between the consecutive dark images occurring during the gradual loading of the specimen.

With K_d known, the photo-elastic method gives the difference, $s_x - s_y$, of the two principal stresses as discussed in the second paragraph above. It also gives the maximum shearing stress directly because the maximum shear stress is equal to $1/2\ (s_x - s_y)$. Hence eq.(9) may be written in the form

$$(s_s)_{max} = nK \qquad (10)$$

where n is an integer. The maximum intensity of light will be obtained when the difference in principal stresses is such that

$$\pi/\lambda\, p(t_2 - t_1) = n\pi + \frac{\pi}{2}$$

By substituting $t_2 - t_1$ from eq. (4) into eq. (7) and then setting

$$K_s = \frac{2\pi c^2}{phe} \qquad (8)$$

one gets

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$$\tau_{max} = \frac{1}{2} n K_s \qquad (10)$$

where $K = K_d/2$. So it may also be stated that there is darkness whenever $(s_s)_{max}$ becomes equal to an integral multiple of K.

Each of the dark fringes in a stressed specimen is the locus of points where the maximum shearing stress or the difference of the principal stresses is constant. By watching the specimen while the load is applied gradually, we may see how the number of dark fringes increases with increase of load. The new ones always appear at the top and the bottom of the beam and gradually move toward the neutral plane so that the fringes become more and more closely packed. The stress at any point is then obtained by counting the number of fringes which pass over the point.

Having introduced some of the basic theory underlying the photo-elastic method of stress analysis, let us consider in more detail the photo-elastic equipment used for quantitative work. The Polariscope, as the apparatus is called, consists of the elements shown in Fig.XIV-C. The source of light may be an incandescent lamp giving white light or a mercury vapor arc lamp giving monochromatic light. The former will give a pattern of brilliant bands of different colors or hues each one representing a constant value for the difference between the two principal stresses. These bands have been designated by the name "isochromatics". The alternate bright and dark lines formed in monochromatic light are also isochromatics (though sometimes called interference "fringes") and are distinguished from one another according to the value of n. consequently, they are often refered to as the isochromatic of zero, first, second order of interference, and so on. The water cooler removes heat energy from the light rays so that the Canada balsam in

[illegible]

[illegible]

[illegible]

points where the maximum shearing stress or the difference of the principal stresses is constant. By watching the specimen while the load is applied gradually, we may see how the number of fringes increases with increase of load. The new ones always appear at the top and the bottom of the beam and gradually move toward the central plane so that the fringes become more and more closely spaced. The stress at any point is then obtained by counting the number of fringes which pass over the point.

Having introduced some of the basic theory underlying the photo-elastic method of stress analysis, let us consider in more detail the photo-elastic equipment used for quantitative work. The Polariscope as the apparatus is called, consists of the elements shown in Fig.XIV-6. The source of light may be an incandescent lamp giving white light or a mercury vapor arc lamp giving monochromatic light. The former will give a pattern of brilliant bands of different colors or hues each one representing a constant value for the difference between the two principal stresses. These bands have been designated by the name "isochromatics". The different bright and dark lines formed in monochromatic light are also isochromatics (though sometimes called interference fringes) and are distinguished from one another according to the order of [illegible] [illegible]

the Nicol prisms will not melt. The purpose of the quarter-wave plates will shortly be discussed.

Returning to a consideration of eq. (6), we see that the amplitude of vibration of light passing through the analyzer is proportional also to sin 2α, where α is the angle between the plane of polarization and the plane of one of the principal stresses (Fig. XIV-A). If these two planes coincide, sin 2α is zero and we obtain a dark spot on the screen. Hence in examining a stressed transparent model in polarized light, we observe not merely the dark fringes discussed before but also dark lines (isoclinics) connecting the points at which one of the principal stresses coincides with the plane of polarization. By rotating both Nicol prisms and marking the dark lines on the image of the stressed plate for various directions of the plane of polarization, we obtain the system of so-called isoclinic lines which join together points with the same directions of principal stresses. Having these lines, we can draw the lines which are tangential at each point to the principal axes of stress. These latter lines are called "the trajectories of the principal stresses". Thus the directions of the principal stresses at each point of the plate can be obtained experimentally.

These isoclinics may be distinguished from the stress fringes by rotating both Nicol prisms alike. The stress fringes do not shift position but the isoclinics do. Usually, however, the isoclinics are removed entirely by inserting quarter-wave plates as shown in Fig. XIV-C. A quarter-wave plate resolves a transverse vibration into two components at right angles to each other; this plate is made of a doubly refracting material such as mica and with such a thickness that it retards one of these components of vibration a quarter-wave length more than the other.

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Returning to a consideration of eq. (6), we see that the amplitude of vibration of light passing through the analyzer is proportional to $\sin 2\alpha$, where α is the angle between the plane of polarization and the plane of one of the principal stresses (Fig. XIV-A). If these two planes coincide, $\sin 2\alpha$ is zero and we obtain a dark spot on the screen. Hence in examining a stressed transparent model in polarized light, we observe not merely the dark fringes discussed before but also dark lines (isoclinics) connecting the points at which one of the principal stresses coincides with the plane of polarization. By rotating both Nicol prisms and marking the dark lines on the image of the stressed plate for various directions of the plane of polarization, we obtain the system of so-called isoclinic lines which join together points with the same directions of principal stresses. Having these lines, we can draw the lines which are tangential at each point to the principal axes of stress. These latter lines are called "the trajectories of the principal stresses". Thus the directions of the principal stresses at each point of the plate can be obtained experimentally.

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The first quarter-wave plate in Fig. XIV-C with its axis at 45° to the initial plane of vibration of the polarized light, produces two component displacements, one parallel to its axis and one perpendicular thereto. These displacements vary exactly in the same manner as the coordinates "u" and "v" of point A moving uniformly on the circumference of a circle (Fig. XIV-B) and for this reason the light emerging from the first quarter-wave plate is said to be circularly polarized. The second quarter-wave plate in Fig. XIV-C restores the plane polarized light if no stressed model is present. An equation similar to eq. (6) can be derived for the vibration of a beam of light after passage through the polariscope including quarter-wave plates and stressed model. The resulting equation differs from eq. (6) in that the term sin 2α has disappeared from the amplitude portion of the expression, showing that the amplitude of the resulting vibration is independent of α and consequently no isoclinic lines are present.

The use of monochromatic light is preferred by most workers for obtaining stress patterns because the dark fringes photograph much more readily and are easier to use than the colored patterns. White light is better for obtaining isoclinics because they show up as dark fringes against a colored background.

<u>The Shear Difference Method</u>

The magnitude of the shear stress (s_s) at any point on any arbitrary straight line across a plane is given by the expression

$$(s_s) = \frac{(s_x - s_y)}{2} \quad \sin 2\theta'$$

where θ' is the acute angle measured from the normal to the arbitrary straight line to the direction of the algebraically maximum principal stress s_x.

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The photo-elastic method provides the necessary and sufficient data to evaluate (s_s). The stress patterns give (s_x - s_y), and the isoclinics give the directions of the principal stresses, i. e., the angle θ'. The numerical values of the shear stress (s_s) can thus be easily calculated at all points.

The above definition of θ' is very convenient because its direction will be the same as the direction of the shear stress s_s.

The following steps outline the procedure for applying the shear-difference method in our work:

1. Draw curves of n and θ' for the edge in question.

2. Determine the direction of s_s by inspection of the θ' curve and by knowing the direction of principal stresses at a particular point along the edge (intersection with upper edge in compression is an example).

3. Compute shear stresses at a sufficient number of points of the edge to permit the plotting of the shear stress curve (s_s). This computation is made by the use of the expression

$$s_s = \frac{s_x - s_y}{2} \sin 2\theta' = nK \sin 2\theta'$$

where values of n and θ' are available from step 1 and K is the fringe constant for the transparent material used and determined as explained previously.

4. A static check is provided by measuring the area under the shear curve with a planimeter or by Simpson's rule, giving an average shear stress. The total shear across the edge is then given by

$$V = (s_s)_{mean} \cdot A$$

where A is the area of the edge section. This value of V is then compared against the actual V.

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B. DETAILS OF PROCEDURE

Polariscope

All of the elements of the polariscope required by this thesis were available in the Experimental Stress Analysis Laboratory. A general view of the Laboratory setup can be seen in Figure XVI, and a skematic diagram of the polariscope is enclosed as Figure XIV.

The polariscope was equipped with sources of both white and monochromatic light which could be interchanged quickly. White light was produced by an incandescent bulb of 500 watts capacity. Monochromatic light was obtained from a d-c mercury-arc. Wratten filters, 58 and 77-A, were used to mask out radiations other than the "green" line. This filter also aided in obtaining sharply defined fringes in the isochromatic diagrams.

The polarizer and analyzer were Nicol prisms and because of their small diameter, a lens system was required to produce a field of sufficient size for studying the model.

Quarter-wave plates were mounted on the same stands as the polarizer and analyzer and were readily accessible and easily removable.

All of the above equipment was mounted on an optical bench. This bench was rigid and the upper surface was free from any projecting brackets or supports so as to permit the continuous uninterrupted sliding of the lenses and prisms resting upon it. The optical bench consisted of two independent parts with the load frame between them. The two sections were aligned and securely fastened in place.

The part before the load frame held the light source, water cell, filter and auxiliary lens, polarizer, quarter-wave plate, and the first collimating lens. The second part supported the second collimating lens,

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The part before the load frame held the light source, water cell, filters and collimating lens, polarizer, quarter-wave plate, and the first [illegible] lens. The second part supported the [illegible] and the [illegible] lens,

second quarter-wave plate, the analyzer, and the camera.

The camera was set on two runners, as was all the equipment on the bench. These runners and the individual supports of each piece of equipment provided for longitudinal as well as vertical movement. Thumb screws could be used to lock the supports in place both longitudinally and vertically. Another set of thumb screws permitted slight transverse adjustment of the polariscope units.

The lens and shutter system of camera were removed, leaving only the bellows. Viewing screens and a polaroid camera were easily inserted at the after end of these bellows providing excellent mobility in focusing and aligning the equipment before photographs were taken.

Although all the equipment required was available, the polariscope had to be set to give the best image for our particular problem.

The first step in the setting of the polariscope was to align the polarizer, analyzer, and all lenses so that their centers lay on one line parallel to the long axis of the optical bench which was checked and found to be horizontal.

The next step was to make sure that the field on the screen was of uniform intensity and well defined. To this end the polarizer was set to give a circularly polarized field and the analyzer to give a bright image on the screen. This called for a mixed setup. The lamp and other elements were adjusted so that the screen field was circular with a sharp outline, and free from color or black blotches.

The elements of the polariscope were then locked into position and these positions were marked along the side of the bench with masking tape.

Load Frame

It is obvious that a suitable straining machine is essential for

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Load Frame

It is obvious that a suitable [illegible] is essential in

photoelastic studies. The problems in a photoelastic laboratory are different from those of a material testing laboratory, and the equipment, therefore, must also be different.

The devices used to apply external loads to a model vary a great deal depending upon individual requirements of special models.

For this thesis a load frame belonging to the Ships Structure Laboratory of the Massachusetts Institute of Technology was used.

A minute description and detailed construction plan for this load frame is found in reference 13.

The load frame is built of aluminum, and its parts are shown schematically in the Appendix.

It is made essentially of a 3/4 inch thick base plate, to which are attached four vertical posts. These posts are made of two opposing channels placed in such a way that a transverse loading bar can work between them.

At the top the vertical posts are attached to a supporting horizontal bar.

The inner posts have holes drilled 1 1/2 inches apart to permit the clamping of the model.

The outer posts have 3/4 inch diameter holes spaced 2 inches apart to permit vertical adjustment of the pivot point of the transverse loading bar.

The pivot pin bears on two bronze bushings placed in matching holes of the outer posts.

The load pin is connected to a sliding attachment on the transverse loading bar.

The whole frame is supported by horizontal roller bearings on a steel I beam. A cross feeding mechanism moves the load frame along the I beam providing for lateral positioning of the model in its own plane.

The beam rests on a steel table having vertical movement. This table is part of the equipment of the Stress Analysis Laboratory.

Thus, both lateral and vertical movement of the load frame can be accomplished easily.

Some modifications were made to suit the particular needs of this experiment.

One of the fundamental requirements for photoelastic work is flexibility and smoothness in loading. In order to determine the general formation of the stress pattern and the fringe orders at a particular point, it is necessary to watch the growing or changing stress pattern under gradually changing loads.

The original frame included a water tank to achieve this varying load. Several authors recommend this weight hydraulic system for smoothest loading.

It was decided, however, that the tank would introduce complications not only because of the required water connections but also because the high loads needed in this problem would cause the deflections of the horizontal bar to become excessive, introducing misalignment in the loading of the plate.

Instead, a hydraulic jack, borrowed from the Ships Structure Laboratory was placed directly over the sliding support of the load pin. The other support for the jack was provided by the upper transverse beam of the load frame.

The whole frame is supported by horizontal roller bearings on a steel I beam. A cross feeding mechanism moves the load frame along the I beam providing for lateral positioning of the model in its own plane. The beam rests on a steel table having vertical movement. This table is part of the equipment of the Stress Analysis Laboratory. Thus, both lateral and vertical movement of the load frame can be accomplished easily.

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Instead, a hydraulic jack, borrowed from the Ship Structures Laboratory was placed directly over the sliding support of the load pin. The other support for the jack was provided by the upper transverse beam of the load frame.

In this manner a higher load could be achieved without the errors introduced by the bending of the bar, and the load could be changed quickly to suit the immediate needs of the experiment. This setup worked pretty well even though some difficulties were encountered in the alignment of the jack itself. By observing the symmetry of the isochromatic pattern obtained, it was always possible to center the applied load.

The vertical channels had to be changed to accommodate the model. The size of the latter was limited by the width of the plate, 12 inches, furnished by the Catalin Corporation. Allowing a margin for the clamping of the model, the distance between the vertical posts had to be reduced to 9 3/4 inches.

This was easily accomplished by boring and threading new holes in the base plate.

This work was done by the Machine Shop of the Institute.

The load was applied to the model by a 1/2 inch diameter cylindrical load pin, acting on the plate through a 3/16 inch diameter load pin. To avoid excessive stress concentration and local plastic deformation, the 3/16 inch pin did not make direct contact with the plate. It rested on a small aluminum bar of 3/4 inch length and of the same thickness as the plate.

In transmitting the load from the small aluminum bar to the plate itself, a thin piece of cardboard with the same dimensions as the bar was used.

This cardboard was used to eliminate a common difficulty present in photo-elastic work, that of the improper distribution of load.

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This cardboard was used to eliminate a common difficulty present in photo-elastic work, that of the improper distribution of load.

In order for the fringes to be continuous and sharply defined, stresses and strains must be two-dimensional. Otherwise, breaks and discontinuities appear in the stress pattern.

To eliminate such discontinuities, the loads must be uniformly distributed across the thickness of the model by means of some equalizer. The simplest equalizer is a piece of cardboard.

The load pin comprises a built-in load cell. This load cell is composed of four SR-4 type A-7 strain gages.

Two of them are placed on opposite sides of the load pin and two are attached to pieces of aluminum bar. The latter act as dummy gages for temperature compensation.

These gages were connected such that they form the arms of a Wheatstone bridge as shown in the Appendix. This setup eliminated any indication of bending and gave a true indication of the axial force through the pin.

These gages were tested for shorts or discontinuities with a potentiometer and were found to be in good operating condition.

The next step was to calibrate the load cell.

For this purpose the load pin was put in series with a Standard Baldwin Load Cell belonging to the Stress Analysis Laboratory.

The load pin gages and its dummies were connected to an SR-4 Baldwin Indicator with a gage factor setting of 1.92.

A calibration curve plotted, indicated a response of 1.058 in/in per pound.

In order to get even numbers, which are easier to work with, a new gage factor setting which would provide an indication of 1.00 in/in per pound was found.

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A calibration curve plotted, indicated a response of 1.098 in/in per pound.

In order to get even numbers, which are easier to work with, a new gage factor setting which would provide an indication of 1.00 in/in a pound was found.

Using the general equation for strain gages indicators:

true x G.F. true = indicated x GF indicated,

we obtain

$$GF\ in = \frac{t \times GFt}{in} \qquad Eq (11)$$

$$GF\ in = \frac{1.058 \times 1.92}{1.00} = 2.03$$

Therefore, a gage factor of 2.03 was used in order to obtain the desired response.

A new calibration run was made using this value for checking purposes.

The calibration curve is shown in the Appendix.

Before each run a zero reading was made and the value of any load could be easily obtained by using the conversion factor of 1.00 in/in per pound.

The precision on the load measurement was dependent upon the minimum resolution of the strain indicator, which was estimated to be about 2.00 in/in.

Photographic equipment

The polariscope arrangement of the Photoelastic Laboratory is that of transmission type, using Nicol prism. This polariscope setup is well adapted for photographic work.

Accurate loading of the model is of prime importance in attaining good results. First the model used was roughly symmetrically loaded, then the loading was adjusted until a symmetrical pattern was obtained.

The sharpness and general appearance of the photoelastic stress pattern was greatly improved by coating the surfaces of the model with

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The actual photographic work was greatly simplified because of the facilities provided on the polariscope setup. The frame of the ground glass viewing screen on the outside part of the bellows is interchangeable with two other frames. One contains a Land Polaroid camera, and another contains a smaller ground glass viewing screen, the same size as the polaroid print and with the same focal distance as the camera itself. The procedure was to focus the picture on this screen, then, exchange this frame for the one containing the camera. The photograph was then taken with no difficulty.

The advantages of the Land Polaroid camera for this type of experiment cannot be over emphasized. To have a picture developed and ready to be analyzed in 60 seconds is a tremendous help when time is at a premium.

As the shutter had been removed from the camera, an improvized shutter had to be devised.

The time of exposure required to photograph a stress pattern depends on many factors, such as intensity of light source, magnification of the image, emulation speed of the photographic film and the transparency of the model.

The improvized shutter was made of two pieces of cardboard rotated manually in front of the light beam. The first trials with the high speed film Polaroid Type 44 were not satisfactory.

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be seen by the photographs obtained. Because of the large size of the model it was not possible to photograph the whole model at one time.

The procedure was to take a picture showing the side boundary and another showing the center part of the model.

Three different pictures were taken for each condition investigated: two of the sides, one with the circular dark field arrangement showing the lines of integral order and another with the circular light field showing the half orders. The third photograph was taken with the dark field arrangement at the center to show the degree of symmetry attained in the loading.

<u>Preparation of Models</u>

The photoelastic material selected for a given model is always the result of a compromise to secure the largest number of desirable properties with the fewest undesirable characteristics. For our experiments Catalin 61-893 (formerly Bakelite BT-61-893) seemed to be the best choice. It has good strength properties, a relatively high modulus of elasticity, and, optically, is moderately sensitive to stress. For stresses below 4000 psi the creep effect is negligible in a period of a few hours. The machining properties are reasonably good, and its time-edge effect is not excessive.

The two Catalin plates ordered from the Catalin Corporation of New York arrived in the unfinished and unpolished state. Several unexpected steps then became necessary before the actual experimental work could be started.

Sketches of the desired tensile model and stiffeners were supplied to the Institute Machine Shop. The Shop machined the model and stiffners to the specifications of these sketches. The tensile model was

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then polished to a smooth and clear finish. All polishing was done on the polishing wheels of the Experimental Stress Laboratory using a solution of aluminum oxide and water as the abrasive. The wheel itself was covered with black Italian velvet.

The plate model was also polished in the above manner. The plate, however, presented added complications as it was noticeably warped. An attempt to remove the curvature by placing the plate in oil, heating to 240°F, soaking at that temperature for a few hours, and then cooling slowly, proved unsuccessful. A second attempt was made by grinding the corners of the plate and heating to 240°F in the small insulated furnace of the Experimental Stress Analysis Laboratory. After several cycles of prolonged heating and gradual cooling with the plate resting on a flat piece of glass, the curvature was removed. Subsequent examination under polarized light showed the model to be stress free.

Horizontal and vertical reference lines spaced one inch apart were etched on the surface of the plate. Finally, a coat of Nujol, a light mineral oil, was applied to the surface of the plate to remove any finger marks and fill in any small scratches.

The stiffeners, because they would not be examined photoelastically, did not require any fine polishing. One SR4 Type A-7 strain gage was mounted on each side of the stiffeners with Duco cement. After the gages were mounted, the stiffeners were placed to dry in the furnace at 80°F for about 24 hours.

Once the first parts of the experiment were over, that is those with the plate in the unstiffened condition, the stiffeners were welded to the models. Penacolite G-1124 was used as the binding adhesive. First the Penacolite was spread on the plate along the vertical centerline

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where the stiffener was to be welded, and also along the edge of the stiffener itself. After a ten minute wait the two were joined in their proper positions. Pressure was then applied and maintained overnight. Two stiffeners were used, one on each side of the plate. The stiffeners were made of Catalin 61-893 and were each 6" x 1/2" x 1/4" in size. A more detailed description of the welding procedure is given in reference 16.

Determination of Fringe Constant

The fringe constant is really a stress-optic constant for the material. It is a property of the material and may vary from batch to batch, as slight differences in curing time and method may easily occur. As the stress magnitude at any point in a photoelastic model is directly proportional to the fringe constant as well as the fringe order, an accurate determination of the former is quite necessary for satisfactory results.

For this reason a tensile model was made and the fringe constant determined by a tensile test. The model was placed in a loading frame as shown in Figure XVIII. The circular polariscope with the dark field arrangement was used and a tensile load was gradually applied to the model. The load was measured by a Baldwin SR-4 load cell connected to a load cell analyzer. At the start a no-load reading was taken. As the load was increased, isochromatic lines appeared as a dark shadow over the entire shank of the model. This shadow appeared, became dark, and disappeared in cycles as the load was gradually increased. The darkest color of each cycle indicated an integral order of interference, and strain readings were taken as each order appeared. After six orders were observed, the load was gradually reduced and readings were taken as

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the orders reappeared. This procedure was repeated and a graph of strain reading in μ-in/in versus order of interference, Figure XIII. was plotted. The slope of this curve was determined as 310 $^{\mu\text{-in}}/_{\text{in}}$/order. Using the formula F.C. = $\frac{1}{b}\frac{\Delta p}{\Delta n}$ equation (12) (where $\frac{\Delta p}{\Delta n}$ is the slope of the curve with 1 lb equal to 10 μ- in/in and b equal to the width of the tensile model in this case .375 inches), the fringe constant was determined to be 82.7 $^{\text{lb}}/_{\text{in}}$- order with monocromatic light of wave length 5461 A°.

Detailed Procedure of Experimental Work

Once these preliminary items were disposed of, the actual experimental work was started.

The unstiffened Catalin plate was placed in the load frame with its bottom edge two inches above the base plate of the frame. The plate was temporarily supported by two rectangular steel bars each one inch thick and placed one on top of the other. Two thin steel plates with flat edges were used on each end of the plate. By placing one of these plates between each side of Catalin plate and the channels of the load frame, better clamping was obtained than would have been possible had only the rounded edge channels been used. The screws were tightened by hand and the model centered between the edge supports. The clamping was then completed by tightening the screws with wrenches. The screws were tightened from the center of each edge outward toward the top and bottom. Approximately equal pressure was put on each screw in an attempt to make the clamping as uniform as possible. The two steel bars beneath the plate were then removed.

The cardboard equalizer and the small aluminum load bar were then centered on the top edge of the plate with the load pin centered hori-

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The cardboard equalizer and the small aluminum load cap were then centered on the top edge of the plate with the load pin centered hard-

zontally across them. The loading arm was then lowered about its pivot point until the vertical load pin on the sliding attachment rested on the horizontal load pin. With the plate clamped two inches above the base plate of load frame, the load arm of the frame was nearly horizontal which made it easier to obtain a symmetrical load distribution.

The hydraulic jack was placed between the sliding attachment of the load arm and the upper cross member of the load frame. Thin wooden blocks were used on each end of the jack to aid in evenly distributing the load. The jack, sliding attachment, and load pin were centered as closely as possible. Pressure was applied to the jack and the load on the model gradually increased until several isochromatic lines appeared on the viewing screen.

Usually the load was not made symmetrical on the first attempt. In these cases, the pressure was released and minor adjustments made to the position of the jack, sliding attachment, and load pin. The pressure was reapplied and the whole procedure repeated until a symmetrical distribution of load was observed. A load of 1650 pounds, enough to give sufficient lines for calculation purposes and still not overstress the plate, was applied.

At this point the large viewing screen was removed and the smaller one inserted. This small screen displayed an image of exactly the same size as that which could be reproduced by the polaroid camera. In addition, if the image was focused sharply on the screen, the same focus would be sharp for the camera. The viewing screen and camera were not large enough to reproduce the image of the whole plate. Separate settings and photographs had to be made for the center and the side.

The model image was centered on the viewing screen by adjusting the

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supporting table and cross feed mechanism of the load frame. The image was sharply focused on the viewing screen, and the screen replaced by the polaroid camera. The load was rechecked and the photograph taken.

In taking the photographs, the exposure time had to be judged by trial and error since the shutter and lens system of the camera had been removed to fit the camera into the bellows of the polariscope. The correct exposure time was achieved by using two cardboard sheets. The two sheets were held flat against each other forming a trianglular slit between them. One sheet was held in front of the quarterwave plate and analyzer while the light excluding slide of the camera was removed. The sheets were then rotated smartly across the light beam until the second cardboard covered the quarter wave plate opening. The slide was then replaced across the camera mouth. After a sixty second wait the picture was removed from the camera.

The load frame was then moved with the cross feed mechanism until the desired image of the plate side appeared on the viewing screen which was now substituted for the camera. The side which gave the clearest image was selected and the above procedure repeated to give a photograph of the integral orders at the side. A 1650 pound load was used for all photographs of isochromatics to allow a better comparison between photographs.

The half order isoclinics were obtained by rotating the polarizer 90° giving a circular polariscope with the light field. These half order isoclinics allowed more points to be plotted on the fringe order curve which was used in the shear difference method computations.

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After the load was released, the equipment was removed and the screws holding the plate were loosened. The Catalin plate was then removed, and the Plexiglass plate was placed in the frame in the same manner.

As isoclinic lines do not vary with load within the elastic limit, the load which gave the clearest pattern of isoclinic lines was applied to the model.

The quarter wave plates were removed and white light through the Wratten filter was used.

The large viewing screen was inserted and focused since tracing paper rather than photographs were used to reproduce the isoclinics.

The symmetry of load was attained by checking that the 0° isoclinic lay along the vertical centerline of the plate. After the load was centered the load frame was moved to the clearest side. Tracing paper was taped over the screen and the reference lines of the plate image were drawn.

The polarizer and analyzer were simultaneously rotated 10° counterclockwise and the 10° isoclinic lines were traced on the paper and labeled. The polarizer and analyzer were rotated 10° more, and so on until a full cycle, 90° was recorded. Intermediate angles were recorded when they appeared necessary for the clarity of the pattern.

This entire procedure for obtaining the isochromatics and the isoclinic lines was repeated for the unstiffened plates supported on the bottom as well as the sides, and for the stiffened plates in both support conditions.

The procedure was varied slightly when bottom support was added. A piece of cardboard was placed between the bottom edge of the plate

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and the base plate of the load frame. While the screws which clamped the sides of the plate were being tightened, light pressure was applied to the plate forcing it against the frame base plate. These two steps were taken in an attempt to insure even distribution of support across the bottom of the plate. The support table for the load frame had to be raised two inches to center the model in the light beam, and the load arm pivot point had to be dropped two inches to permit the load arm to remain nearly horizontal when the load pin rested on the top edge of the plate.

The strain gages attached to the plate stiffener and the dummy gages for temperature compensation were connected forming the arms of a Wheatstone Bridge. A zero reading and subsequent readings as the load was gradually increased to 1650 pounds were recorded. These readings were plotted as strain on stiffner versus applied load as shown in Figure XX.

During the determination of the isochromatics of the stiffened plate with side clamping only, the Catalin plate failed before the 1650 pound load was reached. A loud snap was heard and the load was immediately removed. The plate was examined and a large crack running up from the bottom edge, parallel to the stiffener, was observed. This failure is shown in Figure XIX.

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APPENDIX C

DATA AND CALCULATIONS

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TABLE I

UNSTIFFENED PLATE
Supported at sides only

Station	Order	θ	Sin 2θ	τ
0 (Top)	.80	90°	0	0
1/2	1.23	50.0	.985	179
1	2.15	32.5	.906	287
1 1/2	3.60	27.0	.809	430
2	4.50	25.0	.766	508
2 1/2	5.01	25.0	.766	566
3	5.20	26.5	.799	612
3 1/2	5.20	29.0	.848	650
4	4.89	32.5	.906	654
4 1/2	4.15	37.0	.961	587
5	3.38	37.5	.966	483
5 1/2	2.50	27.0	.809	298
6 (Bottom)	2.00	0	0	0

Applied load at center of plate - 1650 lbs.

Computed shear force on each edge - 744 lbs.

TABLE I

UNSTIFFENED PLATE
Supported at sides only

Station	[illegible]	θ	Sin 2θ	[illegible]
0 (Top)	.80	90°	0	0
1/2	1.23	50.0	.985	173
1	2.15	32.5	.906	287
1 1/2	3.60	27.0	.809	430
2	4.50	25.0	.766	508
2 1/2	5.01	25.0	.766	566
3	5.20	26.5	.799	612
3 1/2	5.20	29.0	.848	650
4	4.99	32.5	.906	654
4 1/2	4.15	37.0	.961	587
5	3.38	37.0	.966	483
5 1/2	2.50	27.0	.809	298
6 (Bottom)	2.00	0	0	0

Applied load at center of plate - 1650 lbs.

Computed shear force on each edge - 744 lbs.

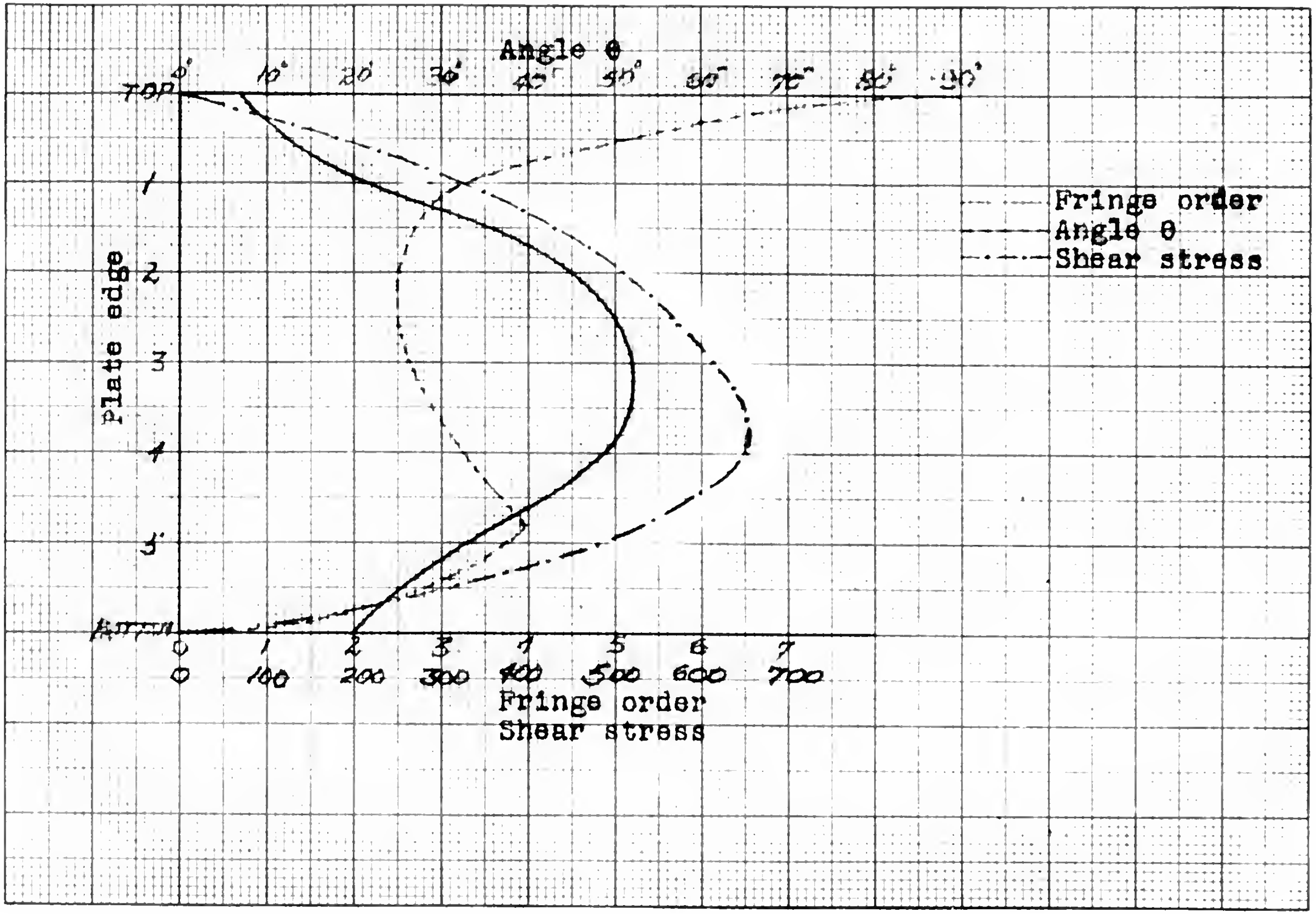


FIGURE II
UNSTIFFENED PLATE
Supported at sides only
Load 1650 lbs.

TABLE II

UNSTIFFENED PLATE
Supported at sides and bottom

Station	Order	θ	Sin 2θ	τ
0 (Top)	0	90	0	0
1/2	1.1	51	.978	158.5
1	2.1	29	.848	262.0
1 1/2	2.9	22	.695	298.0
2	3.1	20	.643	294.0
2 1/2	2.9	21	.670	286.0
3	2.7	25	.766	303.0
3 1/2	2.4	30	.865	306.5
4	2.0	36	.951	280.0
4 1/2	1.6	41	.990	233.5
5	1.2	46	.999	177.0
5 1/2	.7	50	.985	101.8
6 (Bottom)	.2	55	.940	27.7

Applied load at center of plate - 1650 lbs.

Computed shear force on each edge - 382 lbs.

TABLE II

UNSTIFFENED PLATE
Supported at sides and bottom

Station	Order	θ	Sin 2θ	τ
0 (Top)	0	90	0	0
1/2	1.1	51	.978	158.5
1	2.1	29	.848	252.0
1 1/2	2.9	22	.695	298.0
2	3.1	20	.643	294.0
2 1/2	2.9	21	.670	285.0
3	2.7	25	.766	303.0
3 1/2	2.4	30	.865	306.5
4	2.0	36	.951	280.0
4 1/2	1.6	41	.990	233.5
5	1.2	45	.999	177.0
5 1/2	.7	50	.985	101.8
6 (Bottom)	.2	55	.940	27.7

Applied load at center of plate - 1650 lbs.

Computed shear force on each edge - 382 lbs.

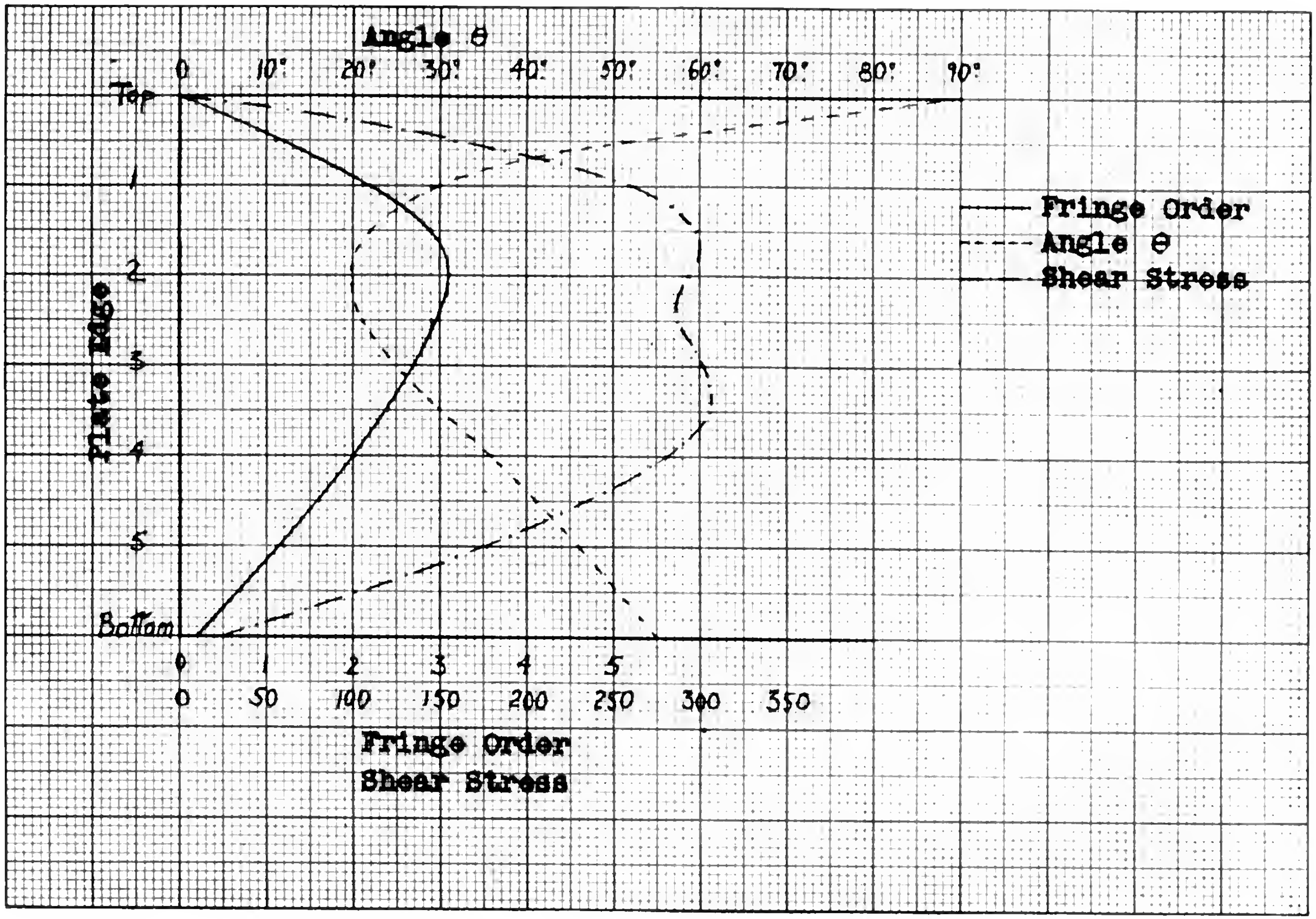


FIGURE III
UNSTIFFENED PLATE
Supported at sides and bottom
Load 1650 lbs

TABLE III

STIFFENED PLATE
Supported at sides and bottom

Station	Order	θ	Sin 2θ	τ
0 (Top)	1.60	90°	0	0
1 2	1.95	59.5	.945	272
1	2.65	48	.970	379
1 1 2	3.27	25	.766	370
2	3.58	20	.643	340
2 1 2	3.65	18.5	.602	322
3	3.30	20.5	.656	320
3 1 2	2.72	30.5	.875	351
4	2.20	39.5	.982	319
4 1 2	1.60	46	.999	236
5	1.20	51	.978	173
5 1 2	0.70	54.5	.945	98
6 (Bottom)	0.00	56.5	.921	0

Applied load at center of plate - 1650 lbs.

Computed shear force on each edge - 451 lbs.

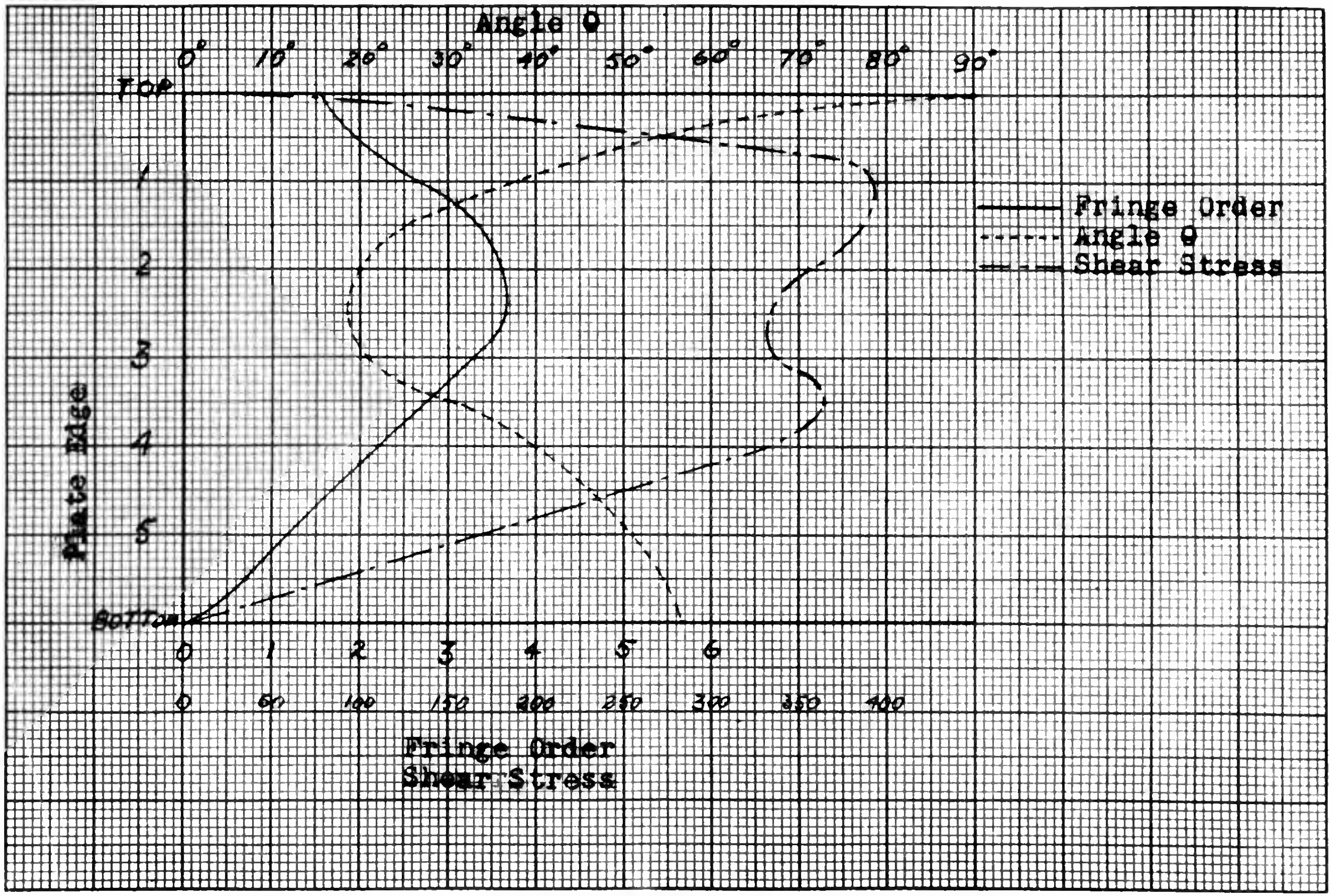


FIGURE IV
STIFFENED PLATE
Supported at sides and bottom
Load 1650 lbs

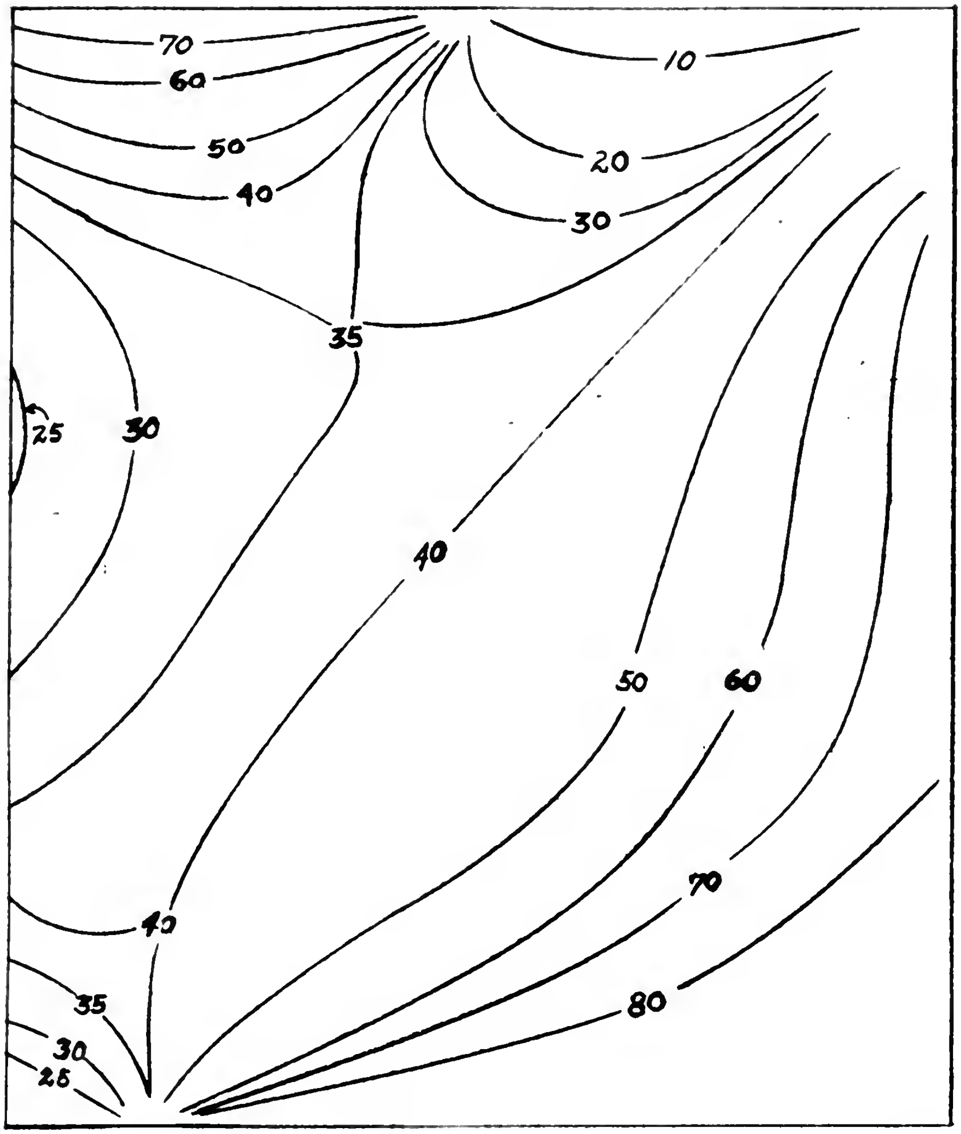


FIGURE V
ISOCLINIC PATTERN
Unstiffened Plate
Supported at sides only

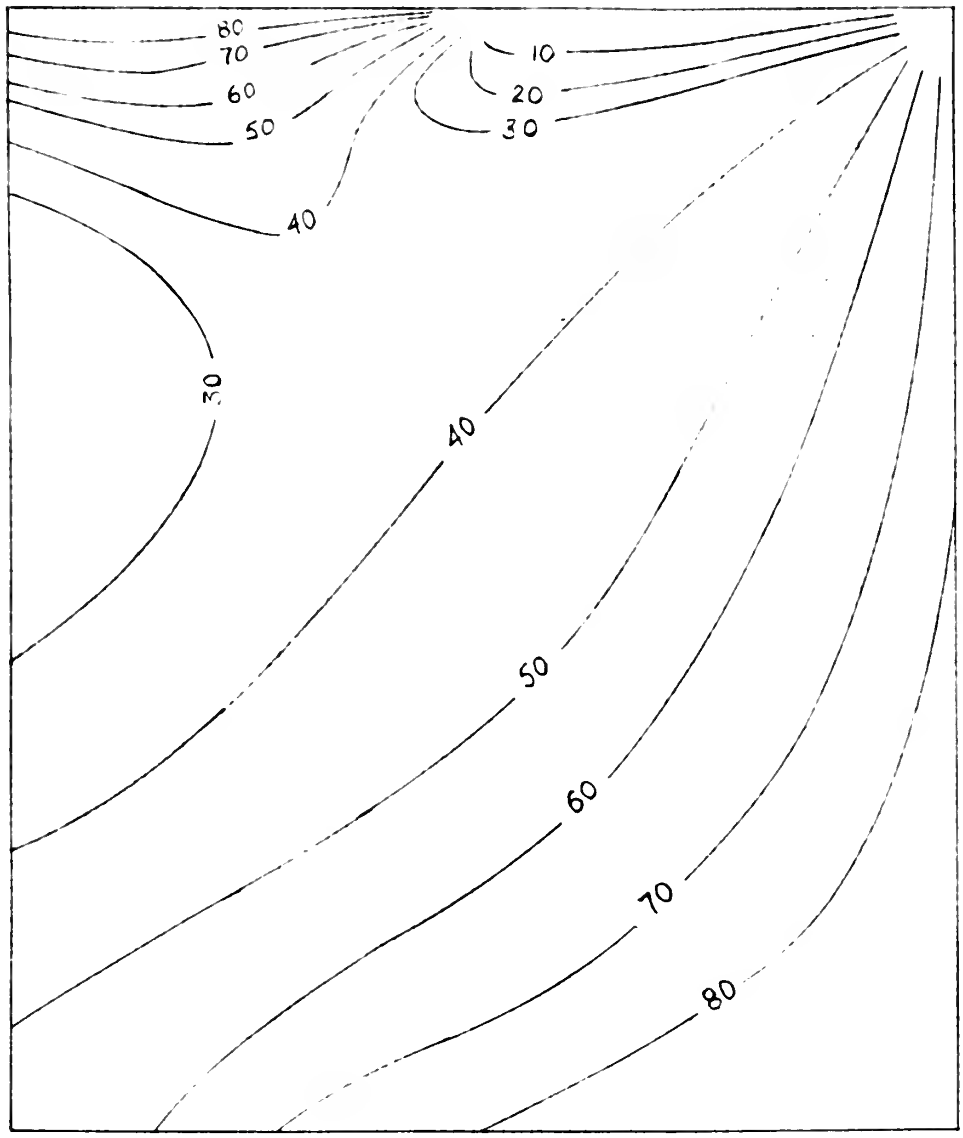


FIGURE VI
ISOCLINIC PATTERN
Unstiffened Plate
Supported at sides and bottom

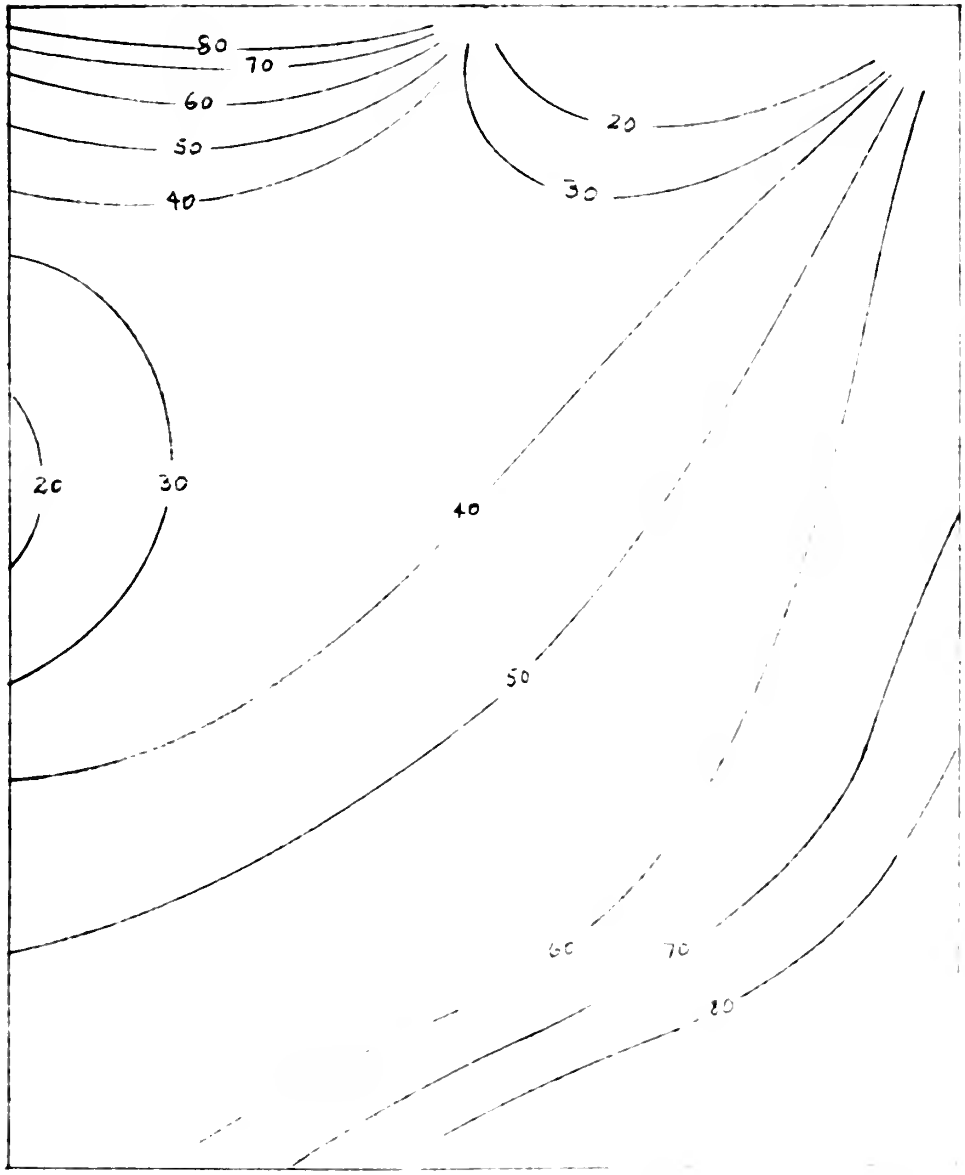


FIGURE VII
ISOCLINIC PATTERN
Stiffened Plate
Supported at sides and bottom

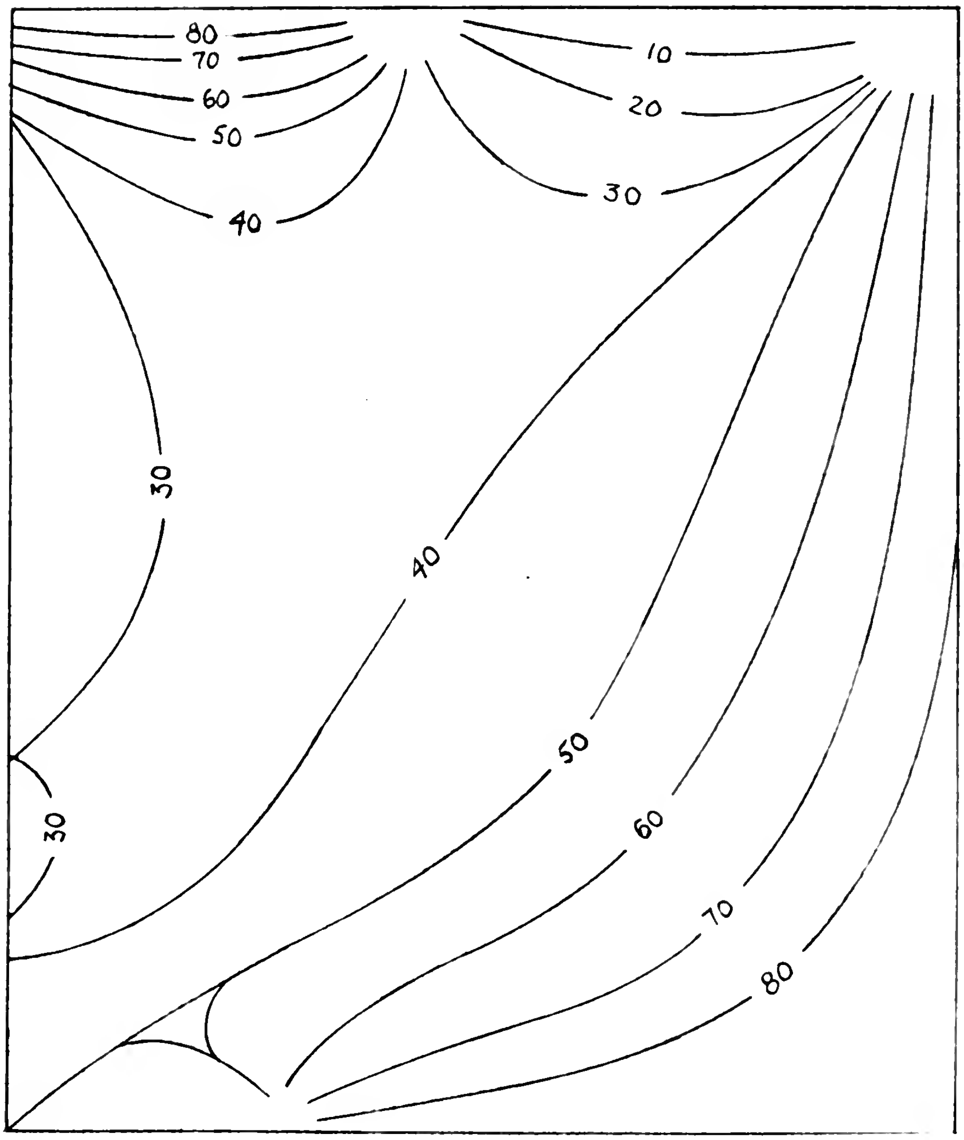
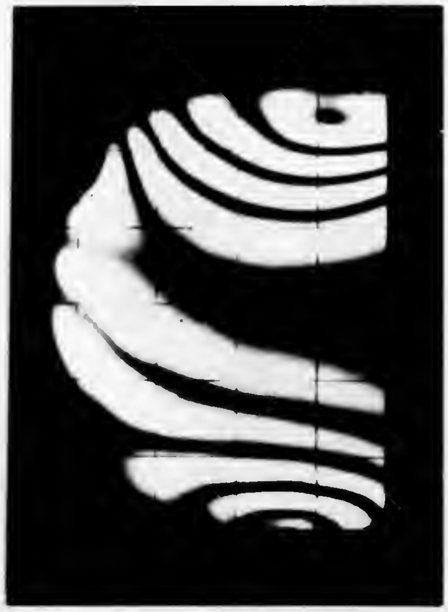
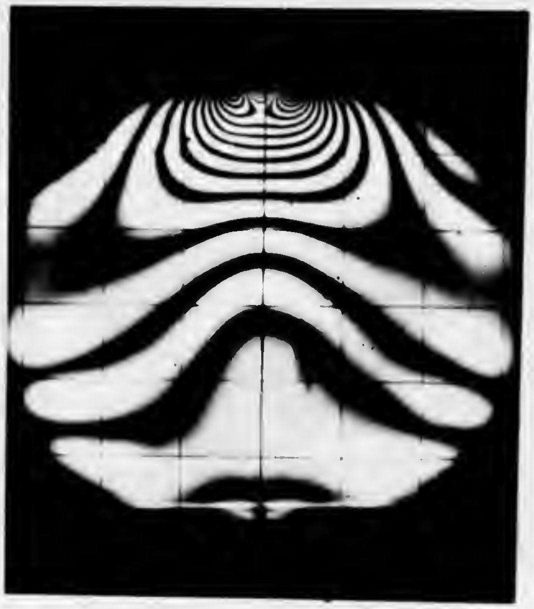


FIGURE VIII
ISOCLINIC PATTERN
Stiffened Plate
Supported at sides only

Edge - Light Field



Edge - Dark Field

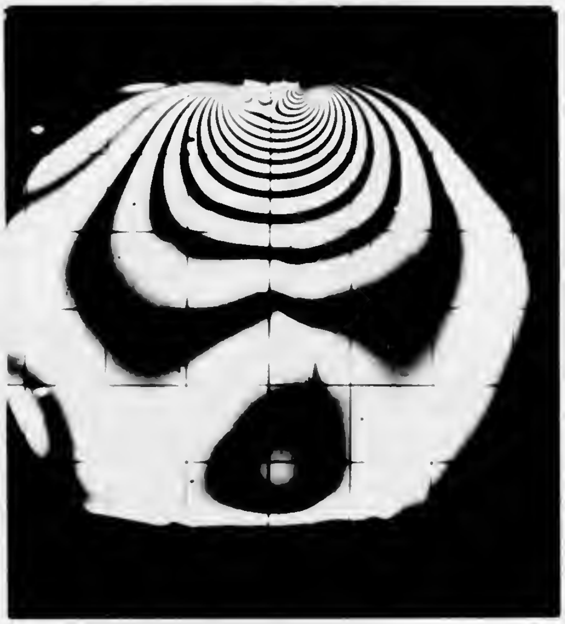


Center - Dark Field

FIGURE IX
ISOCHROMATIC PATTERN
Unstiffened plate
Supported at sides only
Load 1650 lbs.

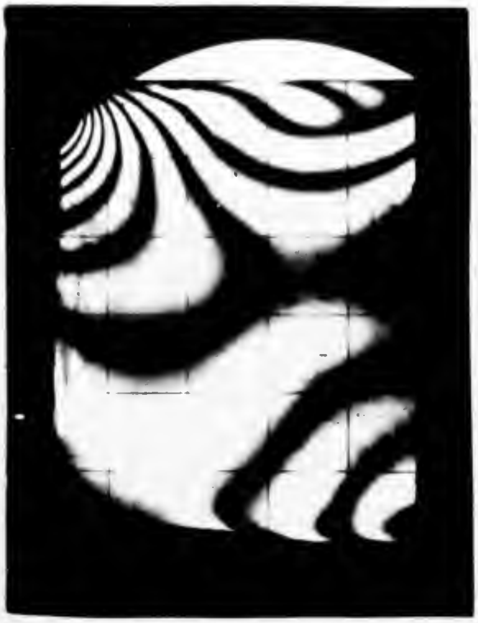
Edge - Light Field

Edge - Dark Field



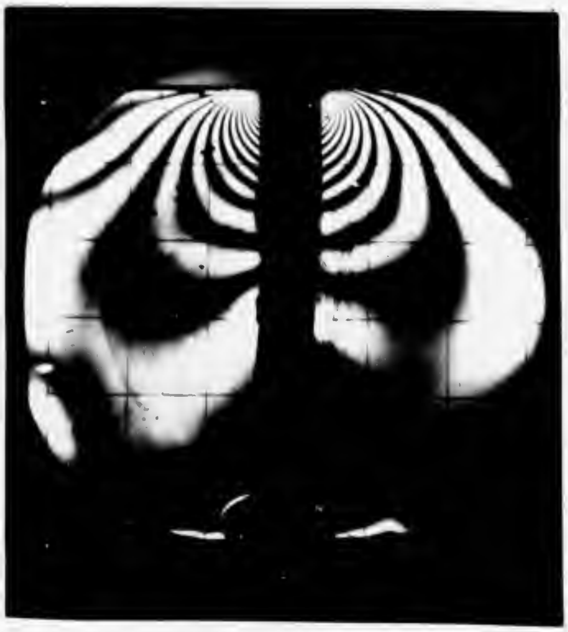
Center - Dark Field

FIGURE X
ISOCHROMATIC PATTERN
Unstiffened plate
Supported at sides and bottom
Load 1650 lbs



Edge - Light Field

Edge - Dark Field



Center - Dark Field

FIGURE XI
ISOCHROMATIC PATTERN
Stiffened Plate supported at sides and bottom
Load - 1050 lbs.

TABLE IV

LOAD PIN CALIBRATION

FOUR SR-4 TYPE A-7 WIRE STRAIN GAGES, G.F. - 1.91

BALDWIN STRAIN INDICATOR SETTING: G.F. - 2.03

Load	Reading	Strain
0	12 - 0527	0
28.5	12 - 0499	28
52.0	12 - 0476	51
62.3	12 - 0464	63
101.0	12 - 0428	99
136.0	12 - 0391	135
173.5	12 - 0355	172
210.5	12 - 0320	207
247.5	12 - 0280	247
267.0	12 - 0261	266
286.1	12 - 0241	286
325.0	12 - 0205	322
368.5	12 - 0160	367
382.5	12 - 0146	381
408.5	12 - 0120	407

Calibration constant - 1.00 μ in/in per pound

TABLE IV

LOAD PIN CALIBRATION

FOUR SR-4 TYPE A-7 WIRE STRAIN GAGES, G.F. - 1.91

BALDWIN STRAIN INDICATOR SETTING: G.F. - 2.03

Load	Reading	Strain
0	12 - 0527	0
28.5	12 - 0499	28
52.0	12 - 0476	51
62.3	12 - 0464	63
101.0	12 - 0428	99
136.0	12 - 0391	135
173.5	12 - 0355	172
210.5	12 - 0320	207
247.5	12 - 0280	247
267.0	12 - 0261	266
286.1	12 - 0241	286
325.0	12 - 0205	322
368.5	12 - 0160	367
382.5	12 - 0146	381
408.5	12 - 0120	407

Calibration constant - 1.00 μ in/in per pound

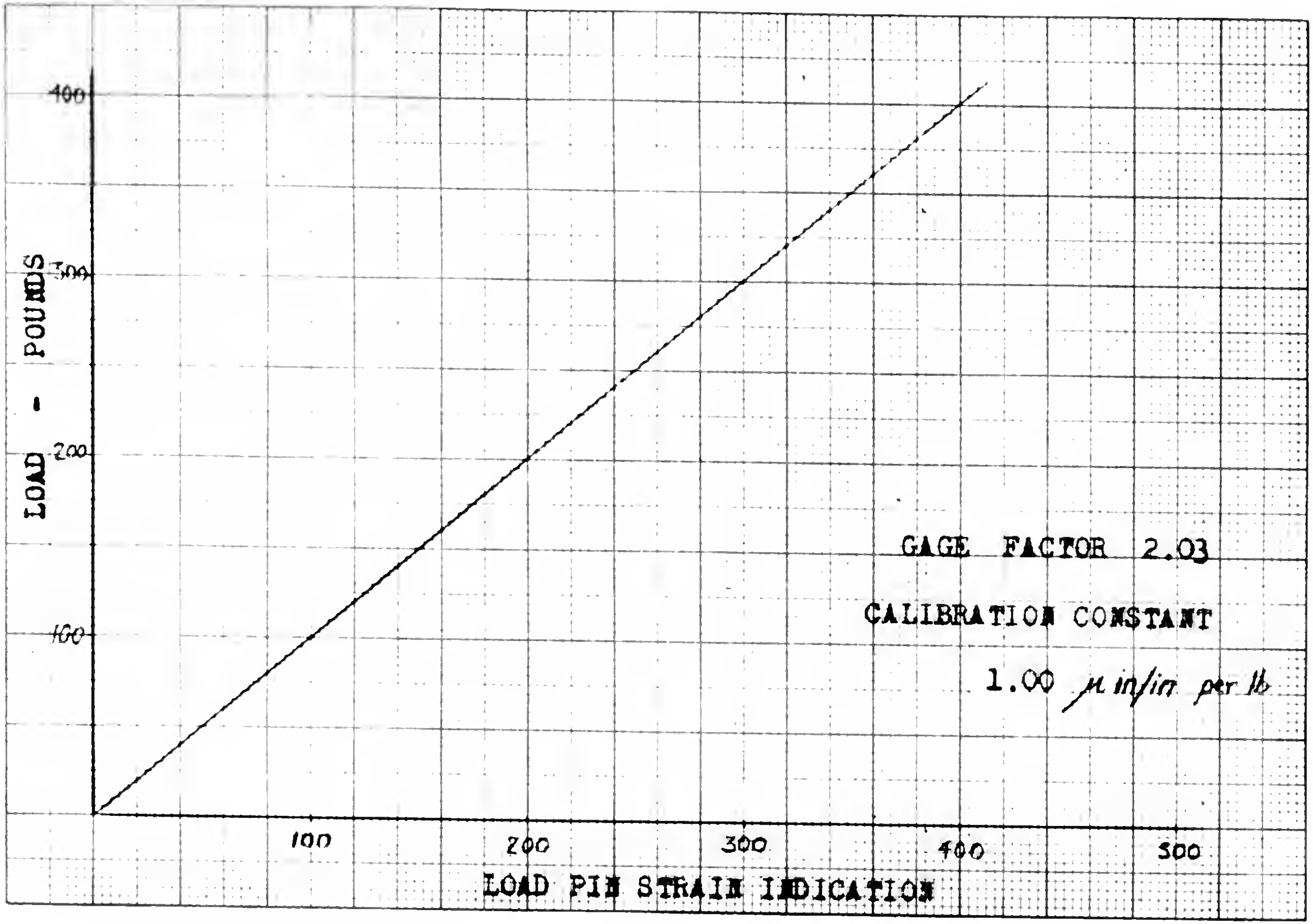


FIGURE XII
LOAD PIN CALIBRATION

TABLE V

FRINGE CONSTANT CALIBRATION

Order	Reading UP	Reading Down
0	10 - 0830	10 - 0825
1	10 - 1130	10 - 1125
2	10 - 1435	10 - 1425
3	10 - 1745	10 - 1750
4	12 - 0047	12 - 0058
5	12 - 0370	12 - 0370
6	12 - 0700	12 - 0700
0	10 - 0815	10 - 0810
1	10 - 1100	10 - 1100
2	10 - 1415	10 - 1410
3	10 - 1710	10 - 1715
4	12 - 0020	12 - 0035
5	12 - 0350	----
6	12 - 0655	12 - 0655

Calbiration Constant - 310 μ-in/in/order

TABLE V

FRINGE CONSTANT CALIBRATION

Order	Reading UP	Down
0	10 - 0830	10 - 0825
1	10 - 1130	10 - 1125
2	10 - 1435	10 - 1425
3	10 - 1745	10 - 1730
4	12 - 0047	12 - 0058
5	12 - 0370	12 - 0370
6	12 - 0700	12 - 0700
0	10 - 0815	10 - 0810
1	10 - 1100	10 - 1100
2	10 - 1415	10 - 1410
3	10 - 1710	10 - 1715
4	12 - 0020	12 - 0035
5	12 - 0350	----
6	12 - 0655	12 - 0655

Calibration Constant - 310 μ-in/in/order

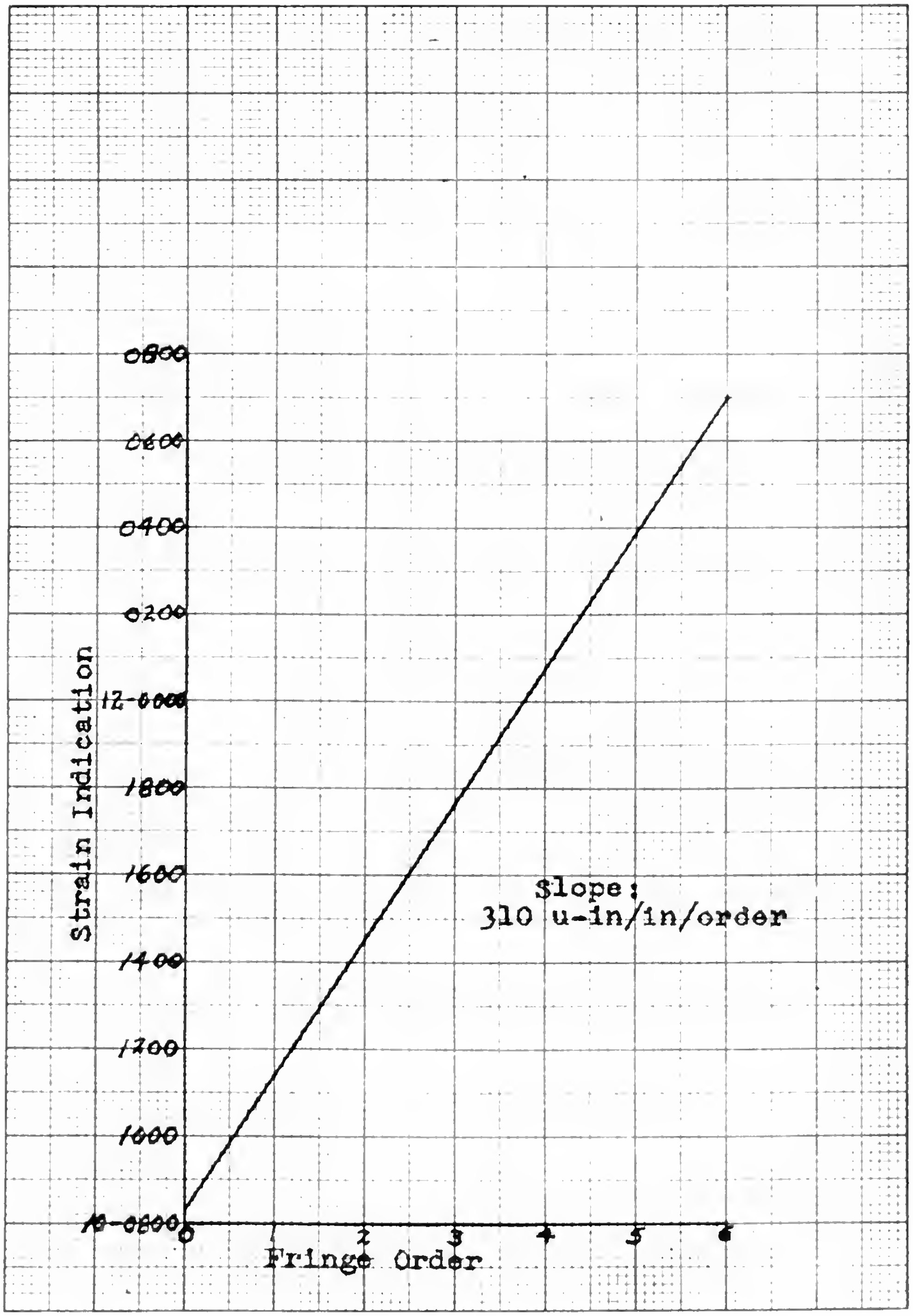


FIGURE XIII
FRINGE CONSTANT CALIBRATION

Figure (A)

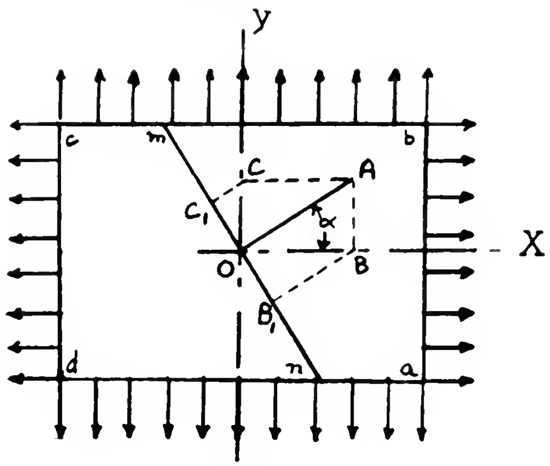


Figure (B)

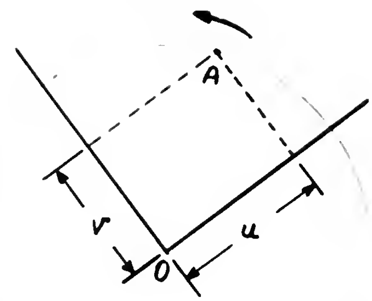
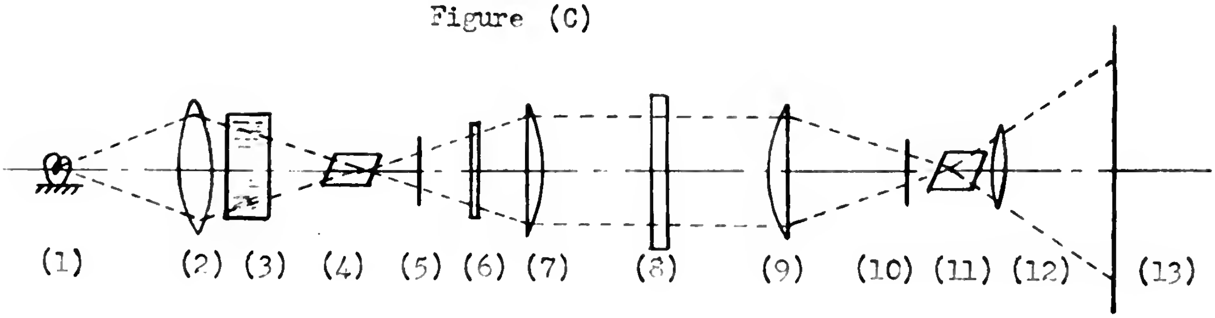


Figure (C)



(1) Light Source
(2) Condensing Lens
(3) Cooler - Jar of Water
(4) Nicol Prism Polarizer
(5) Quarter-wave Plate
(6) Color Filter
(7) Lens
(8) Stressed Model
(9) Lens
(10) Quarter-wave Plate
(11) Nicol Prism Analyser
(12) Lens
(13) Screen or Camera Film

FIGURE XIV

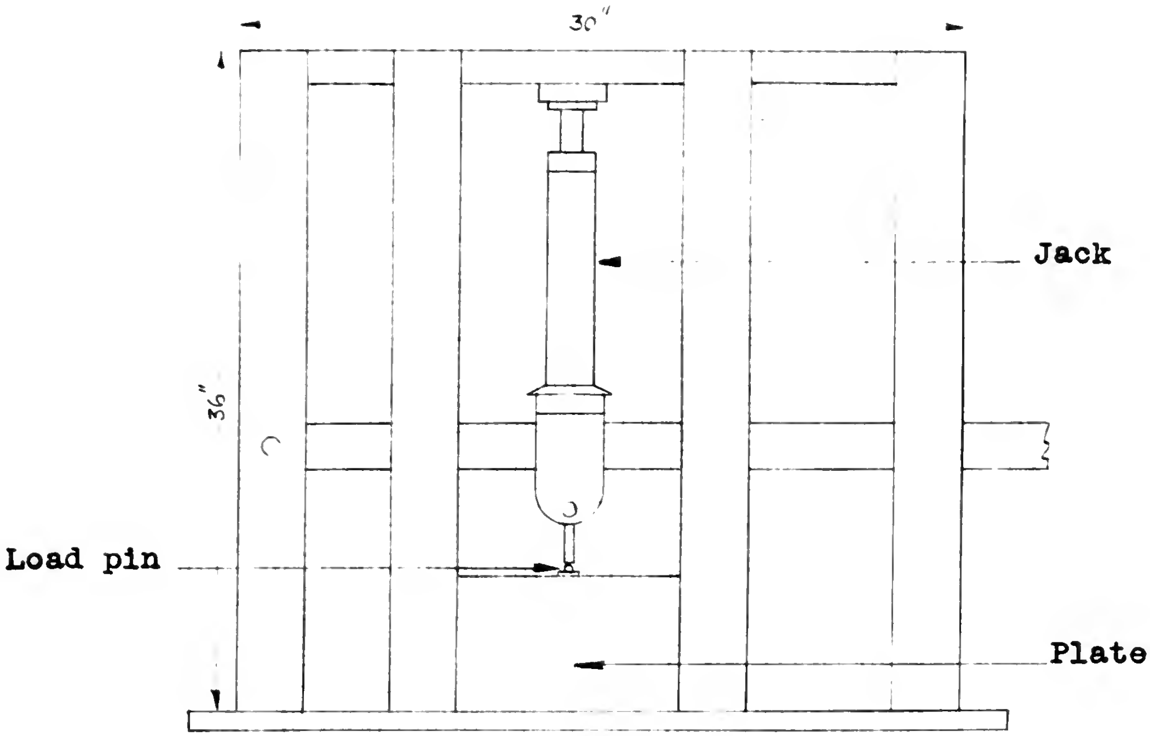


FIGURE XV
SCHEMATIC DRAWING OF LOAD FRAME

PHOTOGRAPHIC ILLUSTRATIONS

FIGURE XVI

General View of Polariscope and
Load Frame

FIGURE XVII

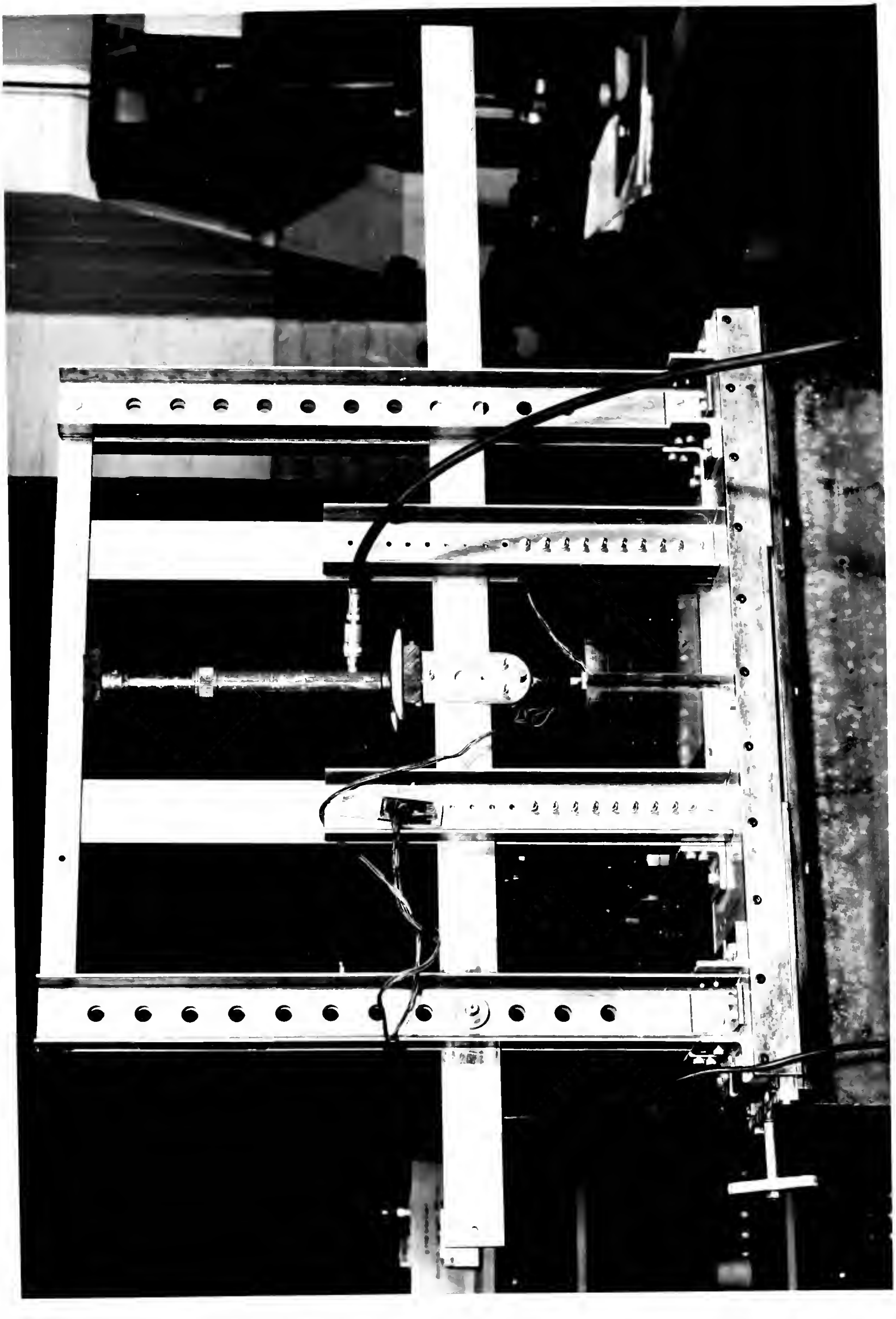
Close-up of Load Frame

FIGURE XVIII

Tensile Model in Macklow-Smith
Loading Machine

FIGURE XIX

Close-up of Stiffened Catalin Plate
Model After Failure
(Note cracks resulting from restraint
caused by stiffner)



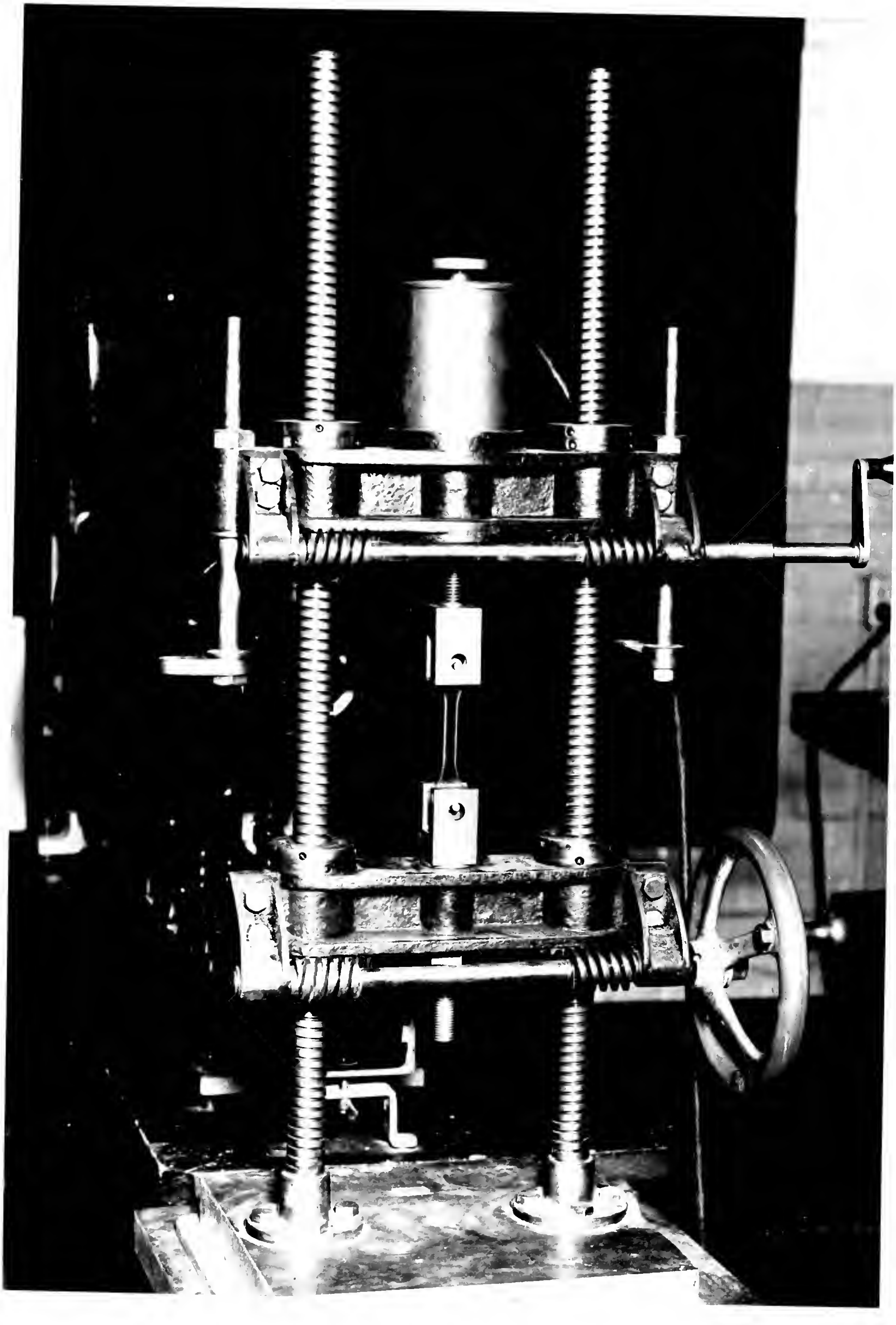


TABLE VI

STRAIN ON STIFFENER

Load		Strain On Stiffener	
Reading	Actual Value (lbs)	Reading	Actual Value (μ in/in)
12-0520	0	2-1025	0
12-0477	45	2-1095	70
12-0410	112	2-1210	185
12-0300	222	2-1370	345
12-0180	342	2-1500	475
12-0120	402	2-1660	635
12-0042	480	2-1730	705
10-1995	527	2-1890	865
10-1870	652	4-0000	975
10-1825	697	4-0030	1005
10-1690	832	4-0295	1270
10-1630	892	4-0370	1345
10-1555	967	4-0500	1475
10-1420	1102	4-0720	1695
10-1370	1152	4-0820	1795
10-1310	1212	4-0910	1885

Gage Factors:

Load Pin - 2.03

Stiffener - 1.91

TABLE VI

STRAIN ON STIFFENER

Load Reading	Load Actual Value (lbs)	Strain On Stiffener Reading	Strain On Stiffener Actual Value (μ in/in)
12-0520	0	2-1025	0
12-0477	45	2-1095	70
12-0410	112	2-1210	185
12-0300	222	2-1370	345
12-0180	342	2-1500	475
12-0120	402	2-1660	635
12-0042	480	2-1730	705
10-1995	527	2-1890	865
10-1870	652	4-0000	975
10-1825	697	4-0030	1005
10-1690	832	4-0295	1270
10-1630	892	4-0370	1345
10-1555	967	4-0500	1475
10-1420	1102	4-0720	1695
10-1370	1152	4-0820	1795
10-1310	1212	4-0910	1885

Gage Factors:

Load Pin - 2.03

Stiffener - 1.91

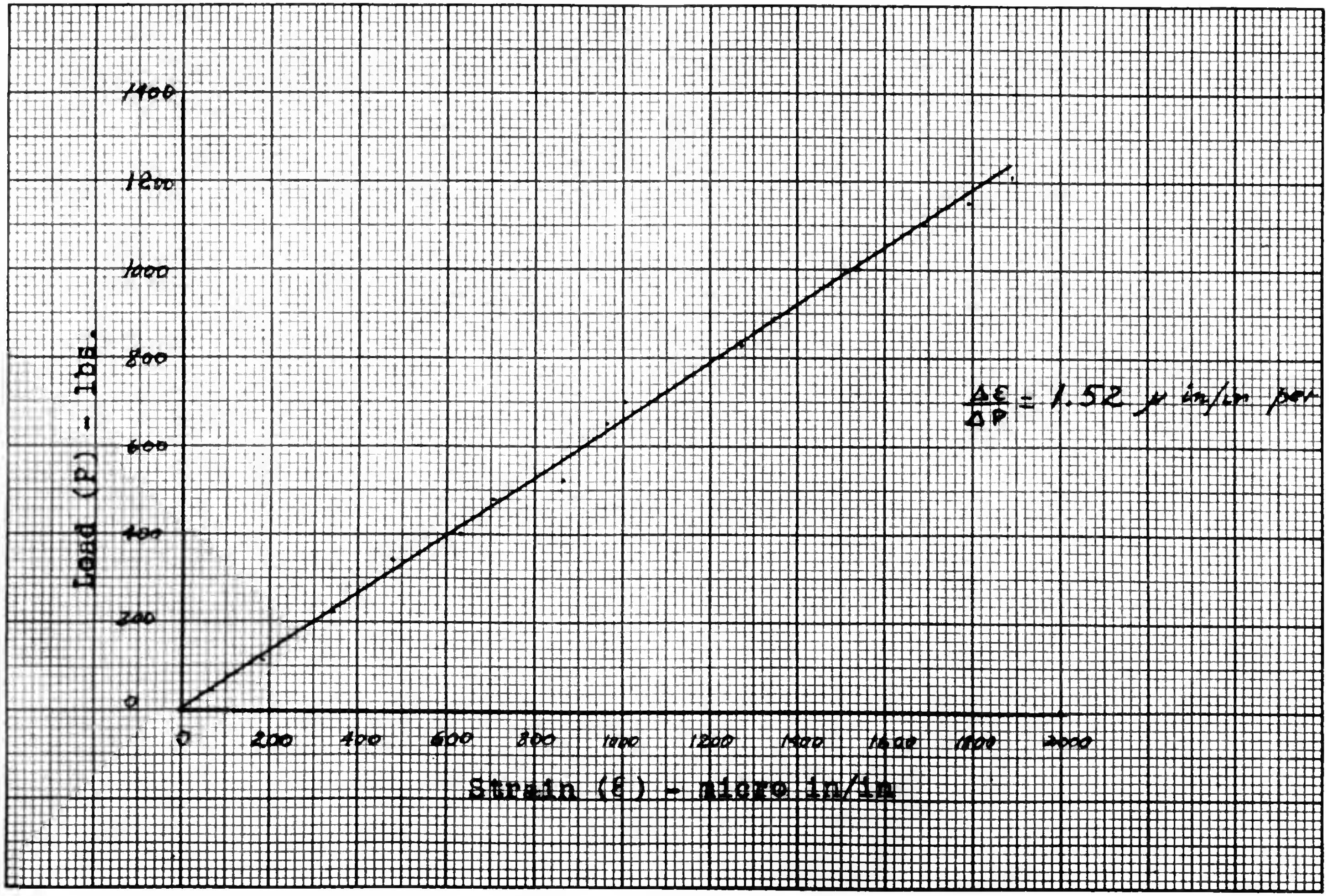


FIGURE XX
STRAIN ON STIFFENER

D. LITERATURE CITATIONS

(1) Ballard, J.A. and Lennon, B.C. "An Investigation of the Effects of Shear on the Compressive Strength of Plating" - Thesis - Dept. Naval Arch. and Mar. Eng.- M.I.T. 1949.

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(3) Bergman, S.G.A. "Behavior of Buckled Rectangular Plates under the Action of Shearing Forces" - Stockolm, Tekniska Hogskolan Avhandling, No. 56 - p. 166+ - 1948.

(4) Brahtz, J.H.A. "Photoelastic Determination of Stresses" - Transaction of the Am. Soc. of Civil Engs. - Vol.102 1937.

(5) Chow, L; Conway, H.D.; and Winter, G. "Stress in Deep Beams", Transactions of the American Society of Civil Engineers CXVIII; p. 686-702, 1953.

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(8) Filon, L.N.G. "The Investigation of Stress in a Rectangular Bar by means of Polarized Light", Philosophical Magazine and Journal of Science, XXIII, p. 1-25; 1912.

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(2) Becker, H. "Photoelastic Analysis of a Spar Bulkhead in a Semi-Monocoque Airplane Fuselage" - Proc. of the Soc. Experimental Stress Analysis Vol. IV - No.I - 1946.

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(8) Filon, L.N.G. "The Investigation of Stress in a Rectangular Bar by means of Polarized Light", Philosophical Magazine and Journal of Science XXIII, p. 1-23; 1912.

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(13) Holman, R. — "A Photoelastic Study of the Stress Distribution in Stiffened Plating" - *Thesis* - *Dept. of Naval Arch. and Marine Eng.* - *M.I.T.* - 1955.

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(16) Phillips, M. M. — "The Tests of Bonding Materials for Bakelite 61-893" *Thesis* - *Mechanical Eng. Dept.* *MIT* - 1948.

(17) Solakian, A. G. — "Photoelastic Models with Cemented Elements" - *Photo-elastic Journal*, *Vol. VI*, *No.1* 1938.

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(14) Murray, W. M. "Class Notes on Experimental Stress Analysis" - Course 2-126 Massachusetts Institute of Technology - 1956.

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